Re-Strengthening Brisbane City Hall: A Case Study of Heritage Engineering

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GraDip AppSc (Building), BEng (Civil)

Submitted in fulfilment of the requirements for the degree of Master of Applied Science (Research)

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November 2013

Abstract

Upgrading old buildings with the evolution of building requirements, this thesis investigates new approaches that can be applied to strengthen our own heritage buildings using historical and comparative analysis of heritage building restorations locally and abroad. Within the newly developing field of Heritage Engineering, it evaluates the innovative Concrete Overlay technique adapted to building restoration of the Brisbane City Hall. This study aims to extend the application of Concrete Overlay techniques and determine its compatibility specifically to heritage buildings. Concrete overlay involves drilling new reinforcement and placing concrete on top of the existing structure. It is akin to a bone transplant or bone grafting in the case of a human being and has been used by engineers to strengthen newer bridges which have suffered load stresses.

This project evaluates the advancements in construction technology, specifically for the upgrading of old building structures to the current building requirements, through the exploration of Brisbane City Hall's most recent restoration program. The structural condition of Brisbane City Hall was examined through its lifecycle and served as the focus of this case study. This thesis was conducted by critically evaluating the ongoing restoration and its intention is to promote public awareness of the resultant value-added structural rehabilitation of Brisbane City Hall.

The restoration of Brisbane City Hall is an indication of a society that acknowledges the significance of cultural heritage. Preserving this historical icon required significant funding support, so the rehabilitation process must be thoroughly analysed and validated. To date, the knowledge and literature for rehabilitating these reinforced concrete heritage structures is significantly lacking. It is hoped that the method of concrete overlay and the case study of Brisbane City Hall restoration will contribute to the development of restoration techniques and policies for Modern Heritage Buildings.

Keywords: *Heritage building; Reinforced concrete; Building restoration; Structural strengthening; Brisbane City Hall*

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Statement of Originality

The work contained in this thesis has not been previously submitted to meet requirements for an award at this (or any) higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT verified signature

Signature:

Arturo Cruz

Date: *5 November 2013*

Acknowledgement

The publication of this thesis would have not been possible without the help and support of many people and institutions, all of whom deserve my thanks and appreciation.

Firstly, sincere thanks to my principal supervisor, Professor Paul Sanders, for his helpful guidance during the research and writing of this paper. It was a great opportunity to work with someone with his experience and dedication to the field of architectural engineering and heritage conservation.

I also wish to thank the overall project manager of the Brisbane City Hall restoration, Mr Jim Mavronicholas for providing archive resources throughout this program and in particular for all the site visits during the renovation of Brisbane City Hall. I also would like to thank the firm Aurecon for their helpful support throughout this year in providing technical details of the structural strengthening of Brisbane City Hall.

Thanks to Mr Randolph Langenbach, leading conservationist in the United States, for his valuable insights regarding the importance of heritage conservation and for showing me some of his works.

Thanks to all my colleagues in the Brisbane City Hall Restoration Scholarship Program, especially co-students Jack Adams and Helen Hall with their corresponding supervisors Dr Mirko Guaralda and Dr Philip Crowther.

Thanks to Illinois Institute of Technology for accommodating me during my research and collection of data about heritage buildings in Chicago, particularly to Professor Peter Land and Emeritus Professor Kevin Harrington of the Architecture and Humanities Faculty and to Dr. Jamshid Mohammadi of the Engineering Faculty. Also, I want to give thanks to Klein and Hoffman Inc. (Structural and Restoration Engineers), Harboe Architects, PC and David Swan for their valuable inputs based on their restoration work in Chicago.

Thanks to Dr. Bob Bryan and the Bryan Foundation for providing this scholarship program, among others, for his philanthropic support.

Finally, I would like to thank my wife Clarissa and my daughter Bernice for their continuous support and encouragement.

1. Introduction

1.1. Background

The Brisbane City Hall, situated in the heart of Brisbane's Central Business District at the corners of Ann Street, Adelaide Street, and Albert Street, is one of the most noteworthy heritage buildings in Queensland as a centre for significant events for over 80 years and has continued to be a favourite hub for both civic and community functions. It was built over a period of ten years between 1920 and 1930 and was designed by local architects Hall & Prentice (Cartwright & Belperio, 2012). The classical stone façade conceals a reinforced concrete structure in the main section, as well as a steel frame construction in the bell tower and dome. Inspired by the neo-classical movement in architecture in Australia, the architectural design of Brisbane City Hall is reminiscent of buildings constructed during the Italian Renaissance, and is based on ancient rule of symmetry. The building is axially configured around the central concert hall with its main architectural features are located centrally on each of the three facades. The clock tower is similar to the design of Venice's St. Mark's Campanile (See Figure 1). The facade was inspired by Palladian Architecture which composed of Corinthian columns at the portico and Ionic columns on the three facades. Externally the building is clad with ashlars stone façades to Ann Street, Adelaide Street and King George Square. The ground floor and exposed basement is clad with locally sourced Enoggera granite, the upper storey is clad with Helidon freestone, local timber for internal joinery and local Darra cement (Heritage Register, 1992). The rear elevation was a rendered brick

Figure 1 Photograph of St Mark's Campanile (L) & Brisbane City Hall (R) (Source: A. Cruz & BCC)

wall that appeared to have been a late change to the design, possibly as a cost saving measure.

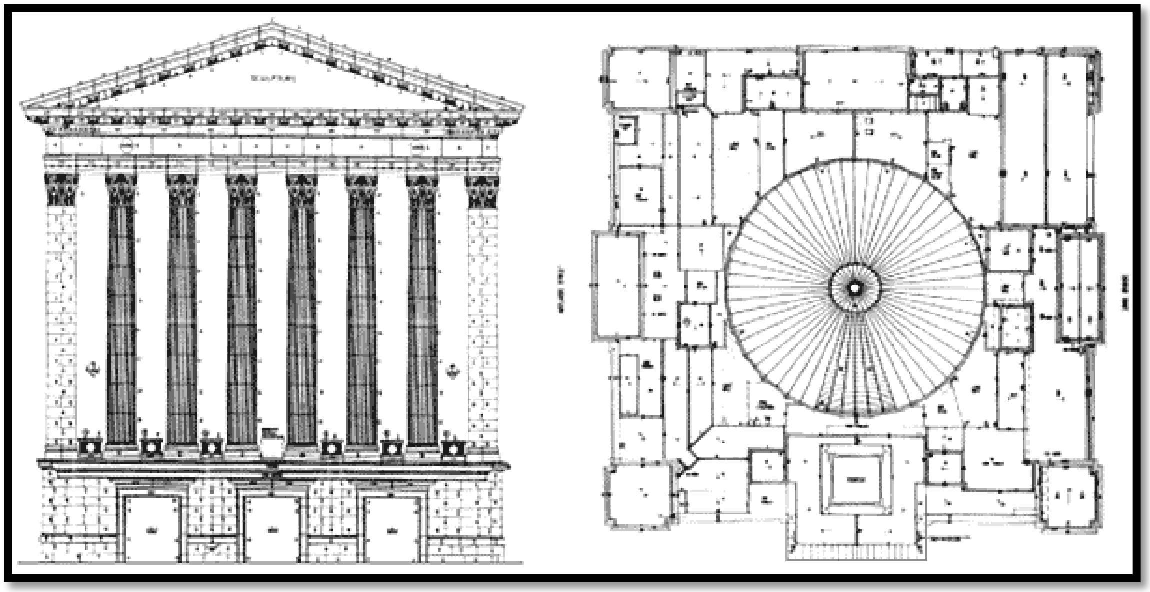

Figure 2 Front Elevation and Plan of Brisbane City Hall (Source:ARCHITECTUREAU)

The City Hall is a four-storey main structure that includes a basement beneath half of its footprint and stands approximately 50 metres high. A circular auditorium in the middle, extending the height of the building, serves as the focal point of four quadrants. The quadrants housed the council chambers, civic offices and the function rooms, and a full height light well was placed in between to separate each section from the auditorium (See Figure 2).

Similar buildings of heritage importance built after the state of Queensland separated from New South Wales in 1859 were the Treasury Building at 21 Queens Street, Brisbane, Customs House at 399 Queen Street, Brisbane, Old Government House at 2 George Street, Brisbane, Parliament House at 69 Alice Street, Brisbane and University of Queensland, Great Court Complex at 12 Upland Road, St Lucia among others (See Figure 3).

Those buildings built at different stages during the development of Queensland have undergone various restorations. The Old Government House had recently been renovated. The Parliament House is currently undertaking minor restorations to the roof. However, during the 1970's a severe termite infestation lead to a major renovation of the main building and again in 1982, Parliament House was renovated at a cost of $13M.

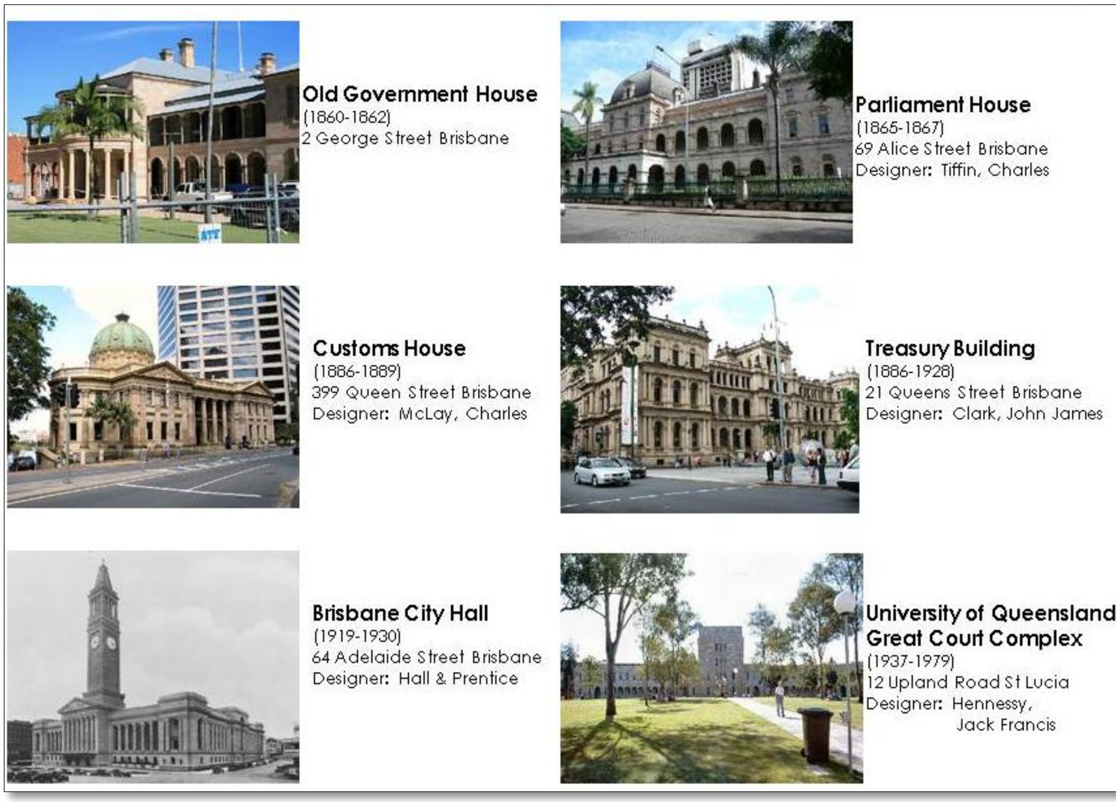

Figure 3 Heritage Buildings in Queensland comparative to Brisbane City Hall (Source: Heritage Register, Department of Environment and Heritage Protection, Queensland Government)

Although the Treasury Building was built earlier than the Brisbane City Hall the construction was done in stages resulting in the completion overlapping with that of the Brisbane City Hall. The first stage of Treasury Building began in 1886 adopting the plan designed by Architect John James Clark. Another architect by the name of Thomas Pye supervised the initial stage which was completed in 1889. Stage 2 began the following year after the tender won by builder John Jude of Adelaide. Stage 2 was completed in 1893. Stage 3 began only in 1922 which required the demolition of the much older Registrar-General’s building in the complex. The entire building was completed officially in 1928. University of Queensland Great Court Complex was designed during the period of 1919-1930 and the construction began in 1939. The construction was halted by the Second World War and work re-commenced by 1948 (Heritage Register, 1992).

1.2. Organisation of the Thesis

Chapter 1 presents the context for the research supported by the literature review which discusses the background of Brisbane City Hall and the philosophy surrounding the processes used for its restoration. This section reveals the lack of documented resources regarding the methods applicable to the conservation of heritage buildings, particularly in relation to the compliance with the existing building regulations, standards and technology. The Research Problem defines the conception of this study while the Aims and Methodology provides discussion that includes the theoretical framework used on the research. Furthermore, this section explains why historical approach combined interviews and comparative analysis were chosen as tools for gathering data in this research.

Chapter 2 describes the details of the main case study and why the restoration was called for. This section enumerated not only the original structural condition and problem of the Brisbane City Hall before the restoration, but also the innovative strengthening method and modern structural analysis adopted for the restoration, that are the main focus of this thesis. Some elements of the literature review are used in this Chapter to explain the technicalities of the structural problem, and the engineering solution applied to the restoration.

Chapter 3 provides comparative analysis among four other heritage structures with similar circumstances that went through restoration. Aside from the similarities of condition, distinctions of approaches were highlighted to reveal the need for streamlining the methods for restoring heritage buildings in spite of the availability of standardised policy and current technology. This chapter also provides justification as to why these buildings are chosen for evaluation as well as its relevance to the case study.

Chapter 4 summarises the results of the research. This chapter also defines the findings that were revealed from the research, interviews and from the comparative analysis that resulted to the Conclusions based on what was asked in the Research

Problem section. Finally, the Recommendation section provides insights as to what this case study further needs to attain its main objective.

1.3. Literature Review

As early as 1992, a comprehensive conservation plan for Brisbane City Hall was prepared by Bruce Buchanan Architects (Buchanan, 1992). Since that time, work has been carried out to conserve the stone façades, the clock tower, and the copper cladding on the dome. In 2001, Brisbane City Council City Design Branch prepared a draft document titled *Brisbane City Hall: Functioning Planning Options, Concepts Stage* (City BCC City Design Branch, 2001). It was followed in 2002 by another draft paper called *Brisbane City Hall: A Strategic Functional Plan for the Brisbane City Council* (Campbell, Lovell, Haycock, Parrish & Cottrell, 2002). This document framed the future direction for restoring Brisbane City Hall.

In 2006, a joint venture involving the consulting groups Cams Consulting Pty Ltd, The Group Development Consultants Pty Ltd and Bruce Buchanan Architects produced “The Brisbane City Hall Master Plan” for review by the City Design Branch of Brisbane City Council (BCC City Design Branch, 2006). Several independent expert consultants were commissioned to investigate the condition of Brisbane City Hall in conformity with the current building requirements. Among them were:

- The Project Services Department of Public Works, which created the City Hall Roof Fire Safety Engineering Model;
- Beca Pty Ltd, who assessed the conditions of the Brisbane City Hall infrastructure and created a report on fire engineering, electrical and hydraulic infrastructure; and
- RMP and Associates, who analysed the City Hall operation and produced the *Brisbane City Council Review of City Hall & Operational Management Report.*

Also among the independent consultants was the firm D. Beal Engineer Pty Ltd, who reported their findings through their “Review of the Concrete Technology and the Design Aspects of Structural Capacity of the Brisbane City Hall” (Beal, 2008). This is a key document of prime interest to this research.

Altogether these reports from independent consultants triggered the commissioning of the City Hall 2010 committee and drove forward to the restoration of Brisbane City Hall (City Hall 2010 Committe Report, 2008).

There has been an increasing interest in the conservation of historical buildings over the past 40 years, primarily because there is a growing civic concern for the cultural significance and heritage value of older buildings (Beames & McKenzie, 1984). While it is often assumed that demolishing old buildings and constructing new state-of-the-art replacements is a more easy option, we have an obligation to conserve the buildings (or places) of cultural significance for present and future generations. “They are irreplaceable and precious” (Australia/ICOMOS, 2000, p 1).

Over the centuries building systems have evolved through the advent of different building materials and components (i.e. stone, pure masonry with mortar, reinforced concrete, timber, etc.). It is necessary to analyse similar structural components and compare their repair systems to fully understand the workings of applying the appropriate restoration techniques in order to comply with the present building requirements. The difficulties in restoring old buildings are well recognised (Badhwar & Kogan, 2008), the challenge for the engineer and the architect is to introduce innovations to strengthen the buildings in a manner that is concealed or at least unobtrusive to maintain the fabric of the heritage structure.

The most significant engineering challenge for the City Hall project was to comply with the current standards while restoring the building with the latest technical innovations. In addition, the provisions stated in the Burra Charter (Australia/ICOMOS, 2000; Beames & McKenzie, 1984; Jordan, 1994) for the conservation of buildings poses an enormous challenge for engineering solutions for restoring heritage structures. The older buildings are not within the scope of the code based standards and requirements for newer buildings anymore. The engineers are required to find a new path to reconcile their proposed solution in compliance with the legislation, as the structural processes used in the past inevitably encounter compliance issues.

There are cases like the Holy Family Church in Chicago where instead of contributing to the overall integrity of the structure, the repairs instead caused further deterioration because the underlying cause was not properly assessed (Crowe, 2007). All too often ongoing building maintenance is limited to only repairing elements that are visibly experiencing distress, hence concealed conditions and causes are often overlooked. Brisbane City Hall, based on the author’s personal observation during site visits, suffered from this problem, i.e. where the previous repairs and restorations were limited only to the surface rather than the underlying structure. One of the objectives of the recent restoration was to undo the previous inadequate repairs and to provide a solution and a full overhaul to give the building greater structural integrity and extra years of working life.

From an engineering point of view, there were occasions when the structural integrity of a heritage building is beyond repair. Engineers have a huge responsibility to public health and safety, as errors by engineers can be fatal. It is therefore imperative that the methods for strengthening of heritage buildings are as good as modern techniques for new buildings. Meticulous structural analysis is needed to avoid errors of faulty strengthening design leading to either over-strengthening the structure (causing unnecessary loss of original fabrics and cultural value) or unacceptable risks to people and heritage (Roca et al., 2010).

This research assumed that structures built within the same period using reinforced concrete technology may have had similar structural problems and rectification strategies to those found in the Brisbane City Hall. The procedures that were implemented on their restorations will further confirm the validity of the strengthening method that was applied to Brisbane City Hall and provide an important reference point on the case studies.

Figure 4 Chicago Board of Trade (built 1930) - a reinforced concrete building that underwent restoration recently (Source: A.Cruz)

Two case studies base in Chicago has been compared to Brisbane City Hall. Chicago comparative analysis was chosen because after the Great Chicago Fire in October 1871, construction of similar types of buildings was booming in the area within the period 1890 to 1930, and this was the age when reinforced concrete construction was at its height (See Figure 4). Concrete has been around for 2000 years but reinforced concrete is relatively new and quite a different sort of material. Reinforced concrete was the invention of Joseph-Louis Lambot in 1848 and later, Joseph Monier, a French gardener, patented a design for reinforced garden tubs in 1876 and later patented reinforced concrete beams and posted for railway and road guardrails. The major developments in reinforced concrete have taken place since the year 1900 (Mallgrave, 2006).

This was also the period when structural steel, as opposed to cast iron and wrought iron, was gaining momentum for use in tall structures such as the new 'skyscraper' offices, apartment blocks and the like. However steel and iron were very susceptible of losing its structural integrity due to fire and corrosion. The versatility of reinforced concrete to be moulded into a desired shape has contributed to its wide usage (Foster, 1982). Despite the increasing popularity of reinforced concrete structures, there were no standards that regulated this kind of construction. It is a different scenario today where the building industry is accustomed to using standard or code based designs. Combined with the available advanced technology, they can manipulate and produce sophisticated structural analysis and techniques such as the "Finite Element Method" (FEM) and modelling (Kurrer & Ramm, 2009; Unay, 2001). FEM is a numerical technique for finding approximate solutions to large number of interrelated boundary problems for differential equations. The introduction of computer made this technique widely used in the structural analysis and design. The use of this technique in the restoration of Brisbane City Hall and will be further discussed in Section 2.

1.4. Research Problem/Motivation

Former Brisbane Lord Mayor (now Queensland Premier) Campbell Newman emphasised that there is a growing awareness in the community about the importance of preserving our heritage structures (Lofthouse, 2011). Brisbane City Hall, a neo-classical reinforced concrete structure, falls within the category of heritage-listed buildings in Queensland Heritage Register, and thus was selected for restoration and preservation. The community explicitly expressed an interest in prolonging the service life of this structure, but the repairs and maintenance were becoming overwhelming. During the three year restoration of this heritage structure, the strengthening of the reinforced concrete has posed a continual challenge to the preservation operators and professionals.

Heritage engineering seeks to find ways to preserve historically important buildings and works for future generations to enjoy. To date, very few studies have investigated the structural restoration of early reinforced concrete buildings as compared to structures built with stone and timber. By examining different practices and innovations from the past to the present, this research was able to confirm that the concrete overlay solution used for the Brisbane City Hall re-strengthening was simply an existing technology applied in a different way to a new kind of project of heritage restoration.

This research contributes new and useful knowledge in the field of heritage building restoration in its assessment of construction methods that will be most feasible and sustainable for heritage engineering work that complies with the existing building codes without sacrificing a building's characteristics. Furthermore, the motivation for this research is to promote greater appreciation of the benefits of building restoration for old and ailing heritage buildings. Irwin (2000) promoted a campaign that whatever affiliation we have in respect to the built environment, we have a professional obligation to the new developing field of heritage engineering. In line with this, it is hoped that this research will promote awareness of the importance of heritage engineering and consequently will find new ways to allow old buildings to be updated with modern standardised requirements.

Restoration jobs are comparatively intricate. It is more challenging to re-strengthen the structure of an old building than to erect a new state-of–the-art replacement in spite of the availability of the more advanced technologies (Kelley & Look, 2005). It can be assumed that the heritage buildings were left behind during the evolution of technology. There is a further issue in upholding heritage buildings with current standards. By exploring the gap between these new technologies and the compatibility with heritage buildings it is hoped that this thesis will contribute to the creation and spread of knowledge in preserving heritage structures.

1.5. Research Aims and Objectives

There has been an explicit effort to ensure the continued and appropriate use of Brisbane City Hall, beginning with the production of "The Brisbane City Hall Master Plan" (BCC City Design Branch, 2006), in order to preserve its life and integrity, and to guarantee its importance and iconic status within the city. In line with this aspiration, this research aims not only to investigate the structural composition of Brisbane City Hall, from its original construction to the subsequent ongoing repairs and maintenance but also to explore some of the innovative approaches used to preserve the building. By examining different practices and innovations from the past to the present, it was intended to determine whether the new techniques of concrete overlay applied in the restoration of the Brisbane City Hall are really innovative or is just an old recycled technology and applied in a different way. This investigation will help to align these new findings and innovations to the development of heritage engineering.

In the specific case study undertaken in the restoration work of the Brisbane City Hall, an innovative technique that was devised to strengthen the structure is analysed and evaluated. This innovative method was to design and test the installation of a structural concrete overlay on top of the existing structural supporting members. This process is new in the sense that it has never been tested in any other historic or heritage building around the globe. Based on a comparison with other similar historic heritage buildings both here and abroad, it was confirmed that this was an unprecedented approach in re-strengthening the structure of a failing heritage building. However some criticism was raised about the compatibility of the strengthening solution, specifically since the old concrete was built in a different time, under different conditions and standards. The~~se~~ combination of old and new materials that may have different compositions and properties which are normally determined from batching and sourcing, would have variations in shrinkage and durability.

This research aims to analyse the significance of the current restoration works on Brisbane City Hall, it also evaluates the importance of retaining and conserving heritage buildings using contemporary strengthening methods. For the purpose of this research, the common problem that contributed most on the deterioration of the concrete structure was identified, documented, compiled and analysed as well as the solution implemented.

The rehabilitation methodologies on structural strengthening used on Brisbane City Hall were also compared to other similarly aged buildings that have undergone similar restorations. These restoration methods were also evaluated for compliance to the existing conservation principles of the Burra Charter. Finally this research will confirm that the restoration works implemented on Brisbane City Hall, or any heritage building in general, is at least compatible with the current building regulations and standards.

This research also explores the notion that the existing Brisbane City Hall did not actually present any risk of structural collapse under its recent functional use, before the restoration. It is also possible that there are more risks that will arise as a result of the current structure being 'disturbed'. To be able to determine that aspect, it will be necessary to review the structural system and condition of the City Hall throughout its lifecycle from initial design, repairs and modifications after this current restoration.

This research will test the compatibility of the current standards, building regulations and technology with that of the case study, furthermore, not only important innovations and improvements were examined but also discrepancies and doubts about methods and systems appropriate for restoring heritage structures that surfaced. The aim is to find the gap between the current standards and building regulations in relation to restoring heritage buildings.

The timing of the initial submission of this thesis is earlier than the completion of the restoration of Brisbane City Hall. Nevertheless, this research will investigate and will provide a clear assessment that the Brisbane City Hall, after $215M (Cartwright & Belperio, 2012) worth of restoration, will be stronger than before and will also comply with the current building requirements and standards. It is the hope of this study to help promote new ways to restore and maintain heritage buildings in order to adapt to current requirements. In line with this, it is also the aim of this research to evaluate the ever evolving standards to evaluate the gap and assess the compatibility with the heritage buildings.

1.6. Research Methodology

The restoration of Brisbane City Hall was used as the main case study. The Research Methodology included combined strategies in this research to assess the state-of-the-art advancements in the structural innovation techniques, and is critically investigated throughout this thesis. It will utilise the mixed-methodology design involving case study combined with interviews with experts, historical analysis and comparative method (Groat & Wang, 2013). It involved collecting and analysing records in connection with the building of Brisbane City Hall; and further required identifying, retrieving and studying past records, plans and specifications in order to determine the original structural condition of the building. There was a large amount of data already available from multiple sources in this restoration project that required careful sorting and categorising. From this historical information, a question arose as to whether or not the building was still in compliance with the current building regulations and standards despite the passage of time.

Regular site visits to the Brisbane City Hall were conducted throughout the duration of this thesis. Interviews with people involved in the restoration work as well as the opinions of experts in the field of conservation were very important aspects of this case study research (Knight & Ruddock, 2009). Hence the main approach that was used in this investigation was to collaborate with the key personnel and primary contractors who were involved in the restoration**.** Valuable opinions and comments from experts in the structural re-strengthening of buildings, both here and abroad, were also obtained to further validate the efficacy of the City Hall restoration project.

People who were informally interviewed, whether in person, by phone and by email, included:

1. Mr Jim Mavronicholas, the overall project manager of Brisbane City Hall
2. Mr Ralph Belperio of Aurecon who is the structural designer
3. Dr Peter Dux of the University of Queensland who proofread the structural design
4. Mr Randolph Langenbach, a leading conservationist and expert member of ISCARSAH (International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage) of ICOMOS (International Council on Monuments and Sites)
5. Mr Gunny Harboe of Harboe Architects in Chicago
6. Mr Donald Friedman of Old Structures PC in New York

These people were selected because the first three were directly connected in varying degrees with the restoration of the City Hall, while the last three independent experts were known for their involvement in research and restoration of heritage buildings overseas. The insights gained during these interviews, focusing on the main research objective, has been the key aspect to the success of developing this thesis and formulating the findings and conclusion. This case study and combined strategies method has been useful in establishing the necessary critical comparisons between other restored buildings overseas and to the Brisbane City Hall.

As most of the current heritage buildings in Europe were made from stone and timber, this thesis has explored buildings in Chicago and California that were more similar to Brisbane City Hall, as it were also built during the same time period. While overseas, interviews with experts yielded important views regarding the ongoing restoration approach adopted at the Brisbane City Hall. The buildings that were compared and analysed, were visited personally by the author in order to validate first hand these opinions in order to confirm or reject the Brisbane City Hall restoration claimed innovation. It has also created an opportunity to contextualise this research on an international comparison level, to explore fully the issues relating to heritage engineering. Hence interviews with experts and comparative analysis methods were used in this case study. This qualitative method and historical approach, in conjunction with my case study has enabled this research to have multiple sources of evidence. This triangulation of strategies complemented each method through comparative analysis.

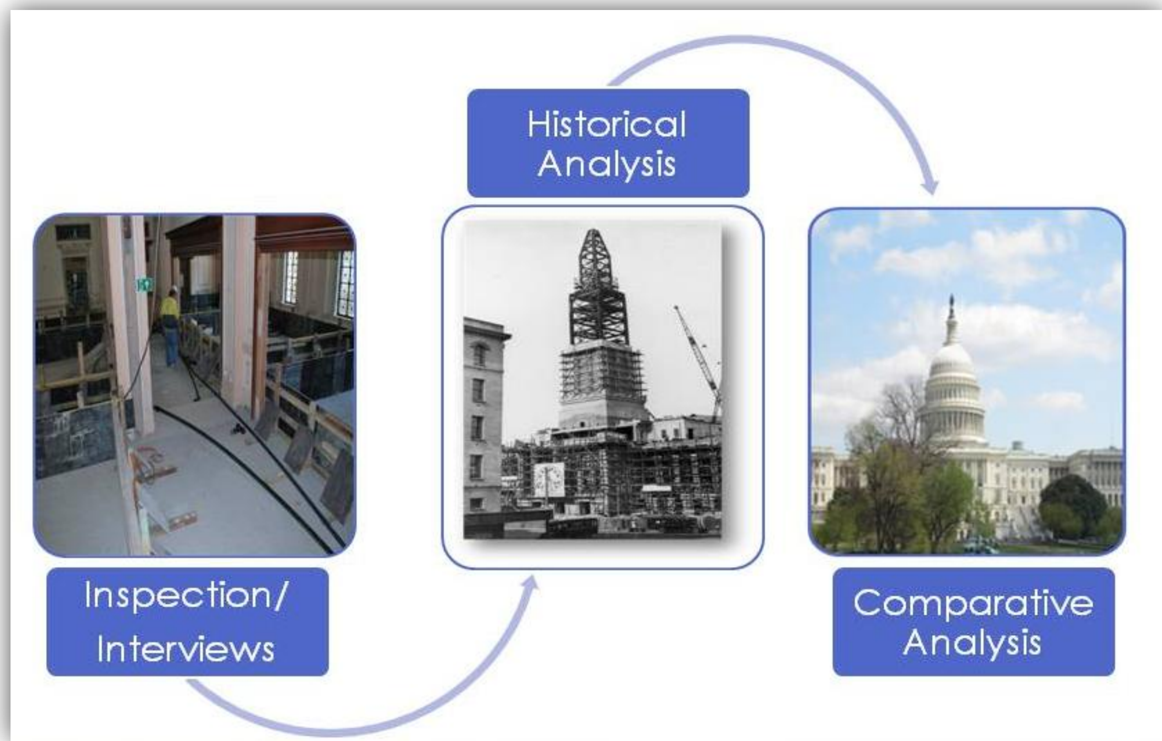

Figure 5 Case Studies and Combined Strategies Approach (Source: The soul of Brisbane, Brisbane City Council and Shutterstock, n.d.)

In line with the case studies and combined strategies method, Roca (2011), and Kelley and Look (2005), have suggested a very holistic method to the restoration of heritage buildings including using a historical approach (See Figure 5). This method involved investigating past records identifying the different aspects and conditions in the initial construction of the Brisbane City Hall. The research also included not only examining modern computational analysis and simulation techniques, but also revisiting the long hand method of structural analysis that was used during the initial design of the Brisbane City Hall. The research explores the compatibility of heritage buildings, not only on the new materials used in this restoration, but also with the technology and standards that are guiding the construction industry today. Although this inquiry is interpretive in nature, the importance of this historical approach as combined strategies highlighted the gap in construction of heritage buildings in today's standards.

2. The Brisbane City Hall Structural Restoration

The Brisbane City Hall has been closed to the public from 2009 to April 2013 in order to accommodate the investigation and the eventual re-strengthening of the building. Previously there had been a view that the building was subsiding and was on the verge of collapsing if no immediate rectification was undertaken. With the use of current innovations in structural engineering, including some patented technologies, rectification has been achieved. This led to, extensive testing and analysis that was performed in order to determine whether the structural capacity of the building was in compliance with current codes and standards. Several problems and their related causes have been identified and documented. One notable problem was the ingress of water to the basement of the building due to the leak coming from the roof. It was claimed that there was a subsequent differential settlement of the foundation where the water was ponding.

2.1. Building Pathology

Figure 6 Photograph showing the original condition of the concrete flat roof (Source: Brisbane City Council)

A view that Brisbane City Hall was sinking became prevalent, and that there was an underground stream below the foundation (Lofthouse, 2011). Media opinion indicated that the cause of the problem was the building's location on a swampy site. In reality, over the years, much of the excess moisture has already been removed as the build-up of neighbouring buildings helped divert the water away.

The main source of water problems that was found came from the roof. A photograph taken a year after Brisbane City Hall opened in 1930, showed the original flat roof (See Figure 6). That physical condition of being flat where water could easily be trapped would be susceptible to maintenance problems. It was recently discovered that the roof was leaking badly due to the limitations of waterproofing system. The major contractor's (ABI Group) project manager, Rod Boxall, explained that they had a problem installing a watertight seal on the surface of the flat roof (Lofthouse, 2011). The floor surface of the rooftop was exposed and it revealed that bitumen membrane was used in the past to protect the floors below from water ingress. The bitumen membrane that was used for waterproofing was originally from Northern Europe where they have a cooler climate. The technology that was used 60 to 70 years ago was not tested against the Queensland climate. However this membrane, once subjected to the harsh climate of Queensland**,** became relatively brittle. Cracks also appeared in the concrete as structural movement occurred. From the weakest point, the water found its way below the barrier until it reached the steel reinforcement of the structure.

From site observations by the author, it was quite evident that previous repairs were just cosmetic and lacked thorough problem analysis that would have led to a substantial solution. As a result, the structure that was added to the roof was demolished because of the leak that was causing serious damage.

During the restoration, former Brisbane Lord Mayor Campbell Newman raised other issues besides re-strengthening the Brisbane City Hall. He stressed that after sorting out the foundation issue, by addressing the drainage problem underneath the building, it allows the improvement of the amenity by relocating the unsightly power transformers and plants and move them within the building.

There was also a concern about the need for a commercial kitchen. "The Brisbane City Hall has never had a proper kitchen during the past. It was quite expensive to run a function room in the building because it would necessitate to bring the food in Brisbane City Hall and double handle it...” (Lofthouse, 2011). The restoration allows the construction of the modern kitchen in the basement.

In addition, they also addressed the fire and safety issues. The main dome over the auditorium had serious fire, safety and structural issues that required addressing. From the beginning when the Brisbane City Hall first opened, bad acoustics were experienced. When it was refurbished in the 70’s, repairs were undertaken that would improve its sound quality but that led to another issue. Fire sprinkler pipes were installed in the ceiling void of the dome. It was later realised that should the sprinkler be activated, the water would be trapped by the ceiling leading to eventual collapse. So if the latest restoration was to proceed, it was prudent to sort out the fire safety and acoustic issues together.

Notwithstanding the above circumstances, the major challenge of the Brisbane City Hall restoration was the structural challenge which required an applicable strengthening method following the guidance of the Burra Charter and the Australia ICOMOS principles. The Burra Charter and the Australia ICOMOS charter for places of cultural significance, advocate a cautious approach to change: “do as much as necessary to care for the place and make it usable, but otherwise change it as little as possible so that its cultural significance is retained” (Australia/ICOMOS, 2000, p 1).

The Brisbane City Hall restoration has been undertaken with a strict adherence to the articles and guidelines of the Burra Charter. The charter is very conservative that it will only permit minimal changes in order to preserve the heritage fabric of the building. This limitation prevents professional adventurism in being able to alter and experiment on places of cultural significance. The charter requires practitioners to consider alternatives and a very delicate approach not common with mainstream construction and repairs.

One significant challenge for restoring the Brisbane City Hall is the fact that it was constructed using reinforced concrete. This structural system has been in use since the late 19th century and became a widely used material in the 20th century. However, it was not until the 1970s that the standards which govern its use were fully recognised and all the good practice requirements that control its usage today were introduced. The use of sea water and calcium chloride as additives during the early reinforced concrete construction are now identified as having a detrimental effect on Brisbane City Hall's long term durability (Macdonald, 2003). These additives increase the rate of corrosion in the steel reinforcement of concrete. What was very challenging was the way reinforced concrete was built that it was difficult to address in many cases without radically changing the building's appearance.

Nevertheless, demolishing the existing Brisbane City Hall and constructing a state-of-the-art replacement was not an alternative option because of its historical and cultural significance. This research aims to validate the value of the restoration, as opposed to building a more modern replacement, by comparing it to other heritage buildings constructed in the same time period and that used the same construction methods.

This major structural overhaul restoration project has required conservationists to devise innovative methods to re-strengthen the ageing reinforced concrete structure without substantially altering the appearance of the building. A new solution was devised that has not been tested anywhere around the globe. This thesis will evaluate that innovation technique and is the subject of this research exploration.

2.2. Structural Make-up of the City Hall

The structure of the City Hall is an in-situ reinforced concrete frame that was a relatively new and versatile material during the time of construction (1920-1930). It was also believed to be a more economical option based on the relatively low construction and maintenance (Gebregziabhier, 2008). The layout of the structure consisted of one way spanning slabs that were supported by a series of secondary beams at 2.2 metre centres and spans at 6.6 metres from the primary beams (See

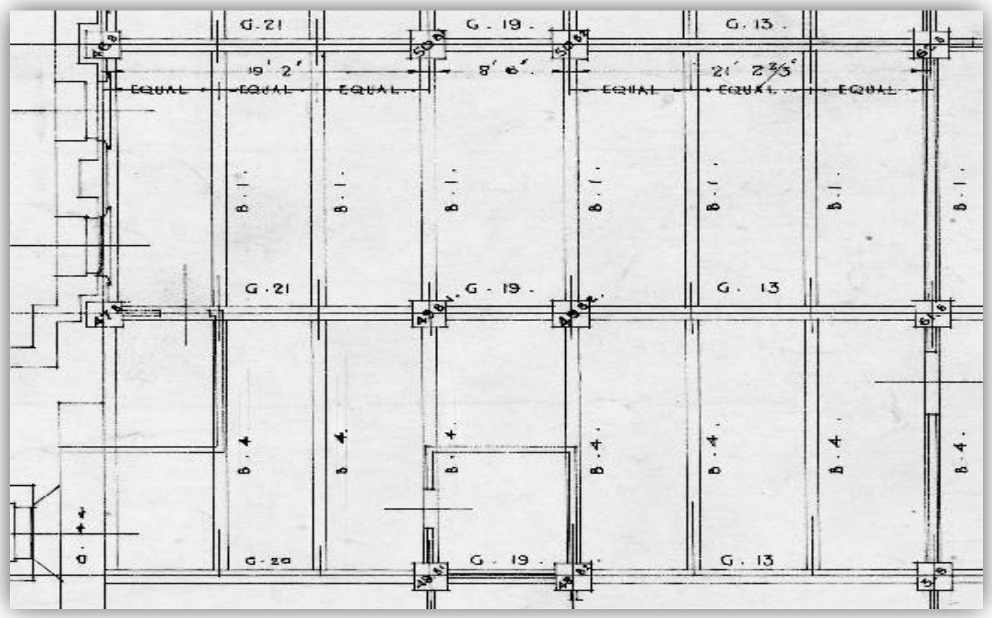

Figure 7 Brisbane City Hall typical floor beam layout (Source: Brisbane City Council, Cartwright & Belperio 2012)

Figure 7 and Table 1).

Table 1 Typical member sizes and reinforcement (Cartwright & Belperio, 2012)

	Primary beam in mm	**Secondary beam** in mm	**Column in mm**
Size	355 wide x 660 deep	280 wide x 585 deep	660 square at ground level reducing to 500 square at the roof
Reinforcement	8 x 28 diameter bars at the bottom and 3 x 12 diameter bars at the top, 10 diameter ligatures	8 x 19 diameter bars at the bottom and 3 x 12 diameter bars at the top, 10 diameter ligatures	12 x 28 diameter bars at ground level reducing to 8 x 28 diameter bars at the roof

The concrete columns were supported by a series of large pier foundations, typically 1500 mm x 1500 mm, which were founded on the underlying weathered rock some 10 to 12 metres below ground level. Before the restoration was started, there was a theory that the building was subsiding, but after analysis it was found that the subsidence was restricted to a limited area of the basement floor slab where leaking drains had washed away the sub-base (Cartwright & Belperio, 2012).

While the stonework was engaged with the concrete frame, it was supported by a reinforced concrete ground beam spanning between the pier footings around the perimeter. The lateral stability of the building was provided by the concrete floor slabs which act as diaphragms to distribute lateral loads to both the façade and the walls around the auditorium, transferring these loads into the foundations. The concrete walls around the various lifts also acted as stability cores.

Although the majority of the structure was a concrete frame designed for gravity loads, two of the most distinctive architectural elements were steel constructions. The first is the copper-clad dome over the auditorium that consisted of a series of lattice trusses with a plate girder compression ring at the crown. The second is the clock tower on the front elevation, facing King George Square. Although clad in sandstone, the structural frame consists of concrete-encased steel plate girders, with diagonal bracing to each face (Cartwright & Belperio, 2012).

The structural design of Brisbane City Hall was constructed using a scientifically-based structural engineering method. While precedent classical (and some early neo-classical) buildings were constructed primarily using the empirical load bearing method of construction, based on traditions and proven observations, most neo-classical buildings progressively took advantage of the advancement in scientific and mathematical innovations that introduced the power of computation into structural analysis. By the early decades of the 20th century modern structural engineering methods were being developed to include the use of a relatively new material such as reinforced concrete. Also during this time engineers and builders, equipped with the growing discovery of mathematical simulation in the field of structural design, were exploring opportunities to construct buildings of comparatively greater height. It was a period when reinforced concrete structures were gaining popularity because of the material's versatility, especially in terms of allowing greater spans and taller buildings (Ressler, 2011). However, at the time the Brisbane City Hall was constructed, there were no building standards regulating the use of reinforced concrete in construction, such as those in existence today (Langenbach, 2012; Macdonald, 2003).

The characteristics and structure of the Brisbane City Hall were different from its European counterparts. During the early years of colonisation, sophisticated building skills were not readily available among the early Australians. While the early buildings in Europe were built by skilled craftsmen, the building industry in Australia fell well short of its contemporaries. Severely lacking were the technical skills and high-grade tradesmen needed to produce fine buildings, that being said, the building industry did benefit from the availability of relatively cheap labour (Dupain & Freeland, 1980; Salmond, 2000). Building the Brisbane City Hall, although innovative in its early structural system, was no exception and it was a product of industrial technology and the evolution of new methods and materials such as mass-produced building components. This exposed the structure to the riskier option of building with economy as the prime consideration.

The advent of reinforced concrete construction in the late 19th and early 20th centuries was taken advantage of by Australia, as a young country in its early days of development. Unlike the pre 19th century where most of the heritage structures and earlier neo-classical buildings were built as masonry and timber structures, reinforced concrete has revealed structural problems which are comparatively more challenging and more complex than found in any other structural systems, especially in terms of re-strengthening (Macdonald, 2003; van der Molen & Alsop, 2000). As heritage buildings such as the Brisbane City Hall age, responsive repairs have been undertaken over the life-cycle of the building to maintain and improve its use over time as well as adapting them to new standards and regulations. These actions although intended to provide significant improvements, instead in many cases generated a greater deterioration of the building, as they themselves become obsolete and were superseded by ever-changing and new technology. The different types of structural problems inherent in reinforced concrete construction became more prevalent and commonplace as time passed.

Another technical problem was the inherently low and wide inconsistency of the strength of the concrete used in the structural members. During a technical site visit by the author, it was observed that there was very little concrete covering the reinforcement and the spalling concrete could easily be disturbed when poked with a stick. This condition indicated severe concrete deterioration and signified that the state of the City Hall was such that it would not comply with the current building regulations and standards.

2.3. The Flat Concrete Roof – the Cause of the Problem

Figure 8 Photograph showing the roof with items that was added over the years (Source: Brisbane City Council)

As mentioned earlier in Section 2.1 of this thesis, the predominant challenge for this restoration is the fact that the Brisbane City Hall is an aged reinforced concrete structure. One of the problems and difficulties in maintenance is that the building has a flat reinforced concrete roof. There was a problem in the roof due to the waterproofing membrane on the roof having failed because it was developed for European conditions, and could not cope with the extreme Queensland weather. Over the years several items in the roof such as the kindergarten school, air-conditioning systems and equipment were added that eventually lead to further maintenance problems (See Figure 8).

As mentioned earlier the failure of the original waterproofing membrane on the roof allowed water to seep into the building. The concrete was porous in places so the water was able to penetrate through the concrete roof. It came into contact with the reinforcement which eventually corroded, as the steel expanded it caused chunks of concrete to spall and break away, exposing the full surface of the reinforcement and eventually undermined its strength and integrity as a structural material.

To mitigate the cause of the problem, it was decided to completely strip back the concrete and apply a new liquid membrane to make sure that there will be no chance of any future water leakage, it will be covered by another layer of waterproofing membrane for additional protection (Lofthouse, 2011).

2.3.1 The Problem of Reinforced Concrete

Figure 9 Reinforced concrete framing construction of Brisbane City Hall in the 1920's (Source: brisbanetimes.com.au)

The Brisbane City Hall was constructed using a reinforced concrete structural system (See Figure 9). Australian buildings were mostly made of reinforced concrete as it was the widely used materials in the 20th century (Irwin, 2000).

Contrary to earlier beliefs, reinforced concrete is similar to other exposed construction materials in a way that it eventually corrodes and deteriorates. When exposed, a reinforced concrete structure is very vulnerable to different forces of nature and other internal stresses. Its resilience is also compromised especially with ever-changing construction techniques and methodologies as in the case of the Brisbane City Hall where its original condition soon lagged behind technology and building standards. Therefore the Brisbane City Hall, given the age of the building, was very susceptible to advanced concrete deterioration because the problems described previously had not been properly mitigated.

However, it was not until the 1970's that the good practice of minimum concrete requirements for reinforced concrete (i.e. concrete cover, length of dowel) was standardised (Macdonald, 2003). Given this situation and the relative absence of specific research on the topic of concrete repairs in heritage buildings, it is more difficult to update such heritage structures as there is not yet a proven and universally accepted technique to resolve strength issues. Existing building standards also posed a significant hindrance to the process of renovating outdated buildings such as the Brisbane City Hall due to the variations between the reinforced concrete materials used then and what is required to be used now.

With the urgent necessity of maintenance work to the Brisbane City Hall, it has been assumed that the aged reinforced concrete shared the same characteristics as the new concrete structures. It was calculated that both old and new building structures will respond similarly to the modern techniques such as structural simulations and standards that the builders were trying to apply during the restoration process. These procedures may still need to be further verified, enhanced and developed for heritage building repairs, as most of the modern techniques have only been used in more recent reinforced concrete structures. This issue is the major focus of this study.

2.3.2 Deterioration of Reinforced Concrete

The report of D. Beal Engineer Pty Ltd (2008) entitled "Review of the Concrete Technology and the Design Aspects of Structural Capacity of the Brisbane City Hall" revealed that the structure was in urgent need of re-strengthening. It was established that the compressive strengths of concrete was very low due to the workmanship oversights from the past which have resulted in decreased strength in the concrete structure of the City Hall building today.

The concrete analysis revealed not only the high water content of the concrete but also the inconsistency of mix throughout. This result was expected, as this would have enhanced the workability of the concrete, a practice that was so common to on-site mixing of early concrete before, as opposed to plant batching of concrete today. As in the case of the Brisbane City Hall, this has led to the detection of higher water content in the fine aggregate mix than in the coarse aggregate, resulting in the bulking of sand, in places which compromised the stability of the concrete.

The electron microscope test revealed that there was a significant lack of hydration crystals, meaning the cement content was relatively less than the aggregate content. This translated to a lower production of bonding since not all the aggregate particles were coated with the hydration product that defines the concrete's compressive strength (Beal, 2008).

Figure 10 Corrosion of reinforcement on Brisbane City Council structure (Source: The Soul of Brisbane)

2.3.2.1 Corrosion of Reinforcement

Besides the inherent low compressive strength of the concrete in the Brisbane City Hall, further visual inspection of the beams and slabs of the building (See Figure 10) revealed numerous issues that also needed to be attended to. It seems that during construction, spacer blocks were not used, the reinforcing bars in the support beams and slabs were as a result barely covered. Spalling of the concrete was also found, particularly in the soffit of the roof slabs where the water ingress was visible. The concrete was comparatively porous in places so the water was able to flow through the concrete from the roof as described earlier.

Many of the durability and service life related problems, both on modern and heritage reinforced concrete building can often be traced to the corrosion of the steel reinforcement. Reinforcing steel was intended to compliment the weakness of the concrete under aggravating tensions brought about in the material under load. It is embedded to ease these tensions but its corrosion eventually contributes to the deterioration and even collapse of the structure. Furthermore it adds to the economic impact of repairing buildings since the cost of refurbishing reinforcement steel in the concrete is comparatively expensive due to having to expose it whilst supporting the structure.

The weakening of the steel reinforcement can be traced back to the lack of integrity of the concrete. When the concrete is exposed to chemical and acid attacks, the material characteristically deteriorates, leading to problems with the steel. Reinforcement steel is also vulnerable to chloride and carbonation that in turn cause the concrete to deteriorate. Once reinforcement corrosion is initiated, it progresses at a fairly steady rate and shortens the durability and service life of the structure. The rate of corrosion directly affects the extent of the remaining service life of a corroding reinforced concrete structure. This rapid deterioration is commonly known as ‘concrete cancer’ (Gebregziabhier, 2008).

Figure 11 Concrete spalling under the beam of Brisbane City Council structure (Source: The Soul of Brisbane)

2.3.2.2 Spalling of Concrete Cover

The spalling of concrete is attributed to the two most common chemical reactions occurring in the lifespan of the concrete known as the alkali aggregate reaction and the other one is carbonation. The composition of concrete is the main factor that leads to its internal degradation. In particular, the presence of undesired impurities is one of the most severe causes of deterioration. For example, the presence of excess sulphate from contaminated aggregate in freshly made concrete can cause severe degradation due to sulphate attack. From the test done by Beal, it revealed that the concrete in the Brisbane City Hall possessed a sulphate content of just under 5% of the weight in the parts that are most likely to decrease the strength of the concrete. The sulphate content in the concrete, although low in the area tested above ground, could still be high below ground level because the sulphate content level in the water table also registered as being high (Beal, 2008). This sulphate (salt) chemically reacts with concrete and in addition to expansion of steel due to corrosion cause damage such as spalling of concrete and the loss of concrete cover that in turn expose the reinforcing steel to further deterioration.

2.3.2.3. Carbonation

$$CO_2 + CA(OH)_2 \rightarrow CACO_3 + H_20$$

where:		
	CO_2	carbon dioxide
	$CA(OH)_2$	calcium hydroxide
	$CACO_3$	calcium carbonate
	H_20	water

Equation 1 Chemical Equation for Carbonation (Source: Standards Australia, 2006)

The reaction of atmospheric carbon dioxide with Portland cement concrete results in the formation of calcium carbonates and, to a lesser extent, sodium carbonates. The chemical equation for the reaction of carbon dioxide with calcium hydroxide produced from cement hydration is illustrated in Equation 1 above.

This reaction is normally referred to as the carbonation process and leads to a depletion of hydroxyl ions in the cement gel and pore solution. The diffusion of carbon dioxide into concrete occurs via the capillary pore structure. Since carbon dioxide reacts rapidly with hydroxides, its penetration into concrete is governed by the barrier of uncarbonated concrete that it encounters. One end of the barrier has a low carbon dioxide concentration due to ongoing reactions within the concrete, whilst the other end, in contact with the atmosphere, is relatively rich in carbon dioxide. A diffusion process results due to the existing concentration difference.

As carbonation proceeds from the exposed surfaces and spreads inwards, it leaves behind reaction products comprised mainly of a hydrated silica skeleton filled with calcium carbonate in concrete made with Portland cement. This layer is stronger and less permeable than the original concrete. The build-up of the carbonated layer increases the resistance to further carbon dioxide penetration. In essence, the initial carbonation acts as a barrier to further deterioration.

While the carbonation process does not unduly affect the durability properties of concrete, the acidity (or alkalinity) level drop can have important implications on the corrosion of the steel reinforcement embedded in the concrete. Extensive carbonation leads to a reduction in the level of acidity, or basidity, of the pore solution within the concrete. Concrete such as Portland cement typically has a level of acidity value in excess of 13, which means it has high alkalinity or base. However this high level of alkalinity is lowered to a value below 10 with carbonation. At a level of values of 10 or less (towards higher acidity), the reinforcing steel is generally no longer passivated and can corrode.

Some shrinkage of concrete may occur as a result of carbonation. The extent of shrinkage depends largely on the concrete's porosity. The normally high alkalinity level environment provided by cement protects the steel reinforcement from corrosion with the formation of an adherent and chemically protective iron oxide surface film. The surface oxide film degrades at values of acidity level to less than 11. With the loss of protection, corrosion of steel can then occur in the presence of oxygen and moisture and generate expansive and disruptive reaction products. These products induce cracking and/or spalling of the concrete cover (Standards Australia, 2006).

Urbanised environment such as Brisbane City contain a relatively higher concentration of carbon dioxide. The rate of carbonation is influenced by the amount of carbon dioxide present in the air. Being such in a relatively high humidity zone, Brisbane also has a disadvantage as ambient moisture also contribute to the rate of carbonation in direct proportion. The disturbance of existing conditions such as the drilling of overlay would have shaken the alkalinity and initial carbonated layers of the heritage concrete, which would have contributed to further deterioration of the existing reinforced concrete.

2.4 Strengthening Method

The preparation of the comprehensive conservation plan for Brisbane City Hall, which had required investigations by several consultants, exposed serious problems in the Brisbane City Hall's concrete structure. The strength and consistency of the hand-batched concrete used in the structural frame of the building when it was constructed was highly variable. Recent testing done by D. Beal and Associates revealed that the characteristic compressive strength was only at 3.4 MPa which is significantly lower than the current minimum standard of 25 MPa required for structural concrete. As a result of this testing, the experts were compelled to further assess the main concrete element of the structure. They further discovered that the steel reinforcement of the concrete would eventually collapse under the prevailing severe stresses. Although the girders that are most susceptible to tension are heavily over-reinforced, this just shifts the mode of failure to over-stressing the concrete in the compressive zone of the beam, which would gradually lead to a catastrophic downfall.

Since the results of the tests proved the building to be significantly below the current concrete structure requirements, it was imperative that strengthening work should be integrated into the renovation strategy for the building. The Aurecon group devised a design methodology to strengthen the floor structure by increasing its capacity with additional reinforcement on the concrete overlays along the weakened areas. The reinforcement was drilled and was held in place vertically by the beams of the structure. This method was subjected to an assessment test done using the prescribed method in AS 3600 (Concrete Structures).

However the non-existence of specific guidance on how to resolve the issue of the existing low-grade structure that falls more than 20 MPa below the Australian Standard prompted Aurecon to involve Civil Engineering Professor Peter Dux from the University of Queensland to verify and validate their proposed strengthening methodology.

2.4.1 Re-strengthening Beams and Girders using Overlays

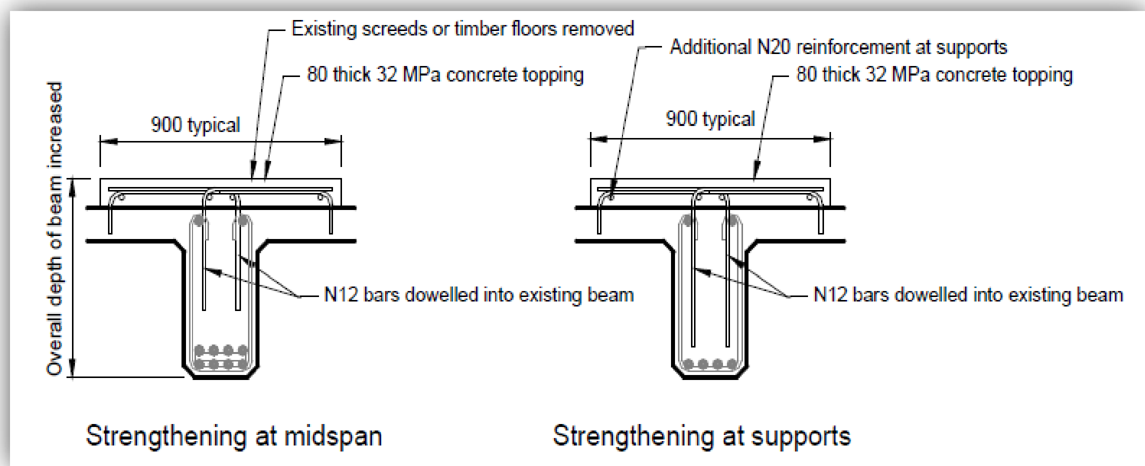

Figure 12 Overlay strengthening details (Source: Cartwright, 2011)

The Aurecon Group devised two methods of strengthening. The first one, an innovative approach, was the provision of an overlay on top of the existing beams and girders. The idea was to increase the strength of the beams by adding additional bending and shear reinforcement in a concrete overlay along the affected length of the beam. The additional steel reinforcement is drilled and epoxied vertically into the existing beams underneath (See Figure 12 & 13).

Figure 13 Photograph showing reinforcement drilled and epoxied vertically into the existing beams underneath (Source: The Soul of Brisbane)

This technique increases the effective depth of the beam at mid-span resulting in a greater rigidity of member that would furthermore decrease the deflection. The vertical dowel bars were drilled into the beams to resist the horizontal shear force between the new and old concrete.

A second method for beam and girder re-strengthening was also introduced. It was undertaken by means of a series of new steel beams situated beneath, and connected to, the under-strength members. The use of either of these methods was governed by the presence of the heritage floor and ceiling finishes that needed to be protected. A heritage floor finish precludes the use of an overlaid solution while conversely a heritage ceiling rules out the use of strengthening steelwork beneath the beams (See Figure 14).

Figure 14 Photograph showing where steel beam lintels could be added (Source: The Soul of Brisbane)

Both methods were chosen and either option was determined by the presence of heritage floor or ceilings.

2.4.2 Strengthening of Columns

For the strengthening of the columns, two solutions were chosen. The first was simply to provide a high strength concrete jacket around the existing profile. This solution is faster, however, in line with the Burra Charter guidelines, was unacceptable as it would increase the overall size of the columns.

Figure 15 Photograph showing columns that require strengthening (Source: The Soul of Brisbane)

The second solution was to remove the outer skin of the column and replace it with a high strength concrete, thus preserving the original size. This option is suitable in the columns along corridors and function rooms, where the increase in original dimensions would be unacceptable (See Figure 15).

A suggestion to insert a steel column into the middle of the existing concrete column was not economically feasible at the current stage of technology.

2.4.3 Earthquake Strengthening

When the City Hall was constructed, earthquake loads were not considered as significant for buildings in Brisbane. Recent expert analysis indicated that the frame on its own lacked sufficient bracing strength. Currently there is a building requirement contained in (AS 1170.4 - 2007) (Structural design actions) and (AS 3826 - 1998) (Strengthening existing buildings for earthquake). The latter code recommends that the horizontal seismic load applied to the existing structure is reduced to 33% of that used in the design of the new structures. This reduction is an allowance for a building's age and the economic considerations arising from the refurbishment and strengthening of existing structures. However there is no special consideration or any additional criteria in AS 3826 specified for heritage buildings.

It is important to note that when using concrete overlays as a strengthening solution, the mass of the building will relatively increase and this makes it more vulnerable to earthquakes and overloading in direct proportion. This view was shared by ISCARSAH expert Randolph Langenbach during an interview conducted by the author. Considering all these factors, the structural engineers, Aurecon, ruled that it was not considered appropriate to upgrade all aspects of the structure in accordance with AS 3826. This decision was in consideration of the heritage impacts and the seismicity of the Brisbane area, among other factors. Hence to overcome this issue it was decided only to restrain the high risk elements of the structure. The strengthening work eventually undertaken, took the form of new concrete walls cast immediately against the face of the existing brickwork. These concrete walls are located adjacent to the foyers and light wells.

Figure 16 New steel structures designed to restrain the existing high stone parapets (Source: A. Cruz)

At roof level, the use of a steel structure for the new Museum of Brisbane is intended to restrain the existing high stone parapets. It was also indicated that additional works will be carried out on the clock tower to ensure that the balustrades and finials are adequately restrained (Lofthouse, 2011).

2.5 Analysis using State-of-the-Art Technology

Designers and engineers are now universally accustomed to using computer modelling and the contemporary available standards in construction (Groak, 1992; Roca et al., 2010; Roca et al., 2005). These techniques are a far cry from the old long hand structural calculation methods, and previous absence of building standards back in 1920, when Brisbane City Hall was built originally.

For this restoration, structural analysis carried out by Aurecon used the state-of-the-art computer modelling and the most up-to-date available standards for their investigation. However, it is important to note that the current available concrete standard explicitly states Section 1.1.1 (page no 8) of AS 3600 “This Standard applies to structures and members in which the materials conform to concrete with characteristic compressive strength at 28 days in the range of 20Mpa to 100 MPa...”(AS 3600 - 2009). The test results revealed that all of the samples fell below this range.

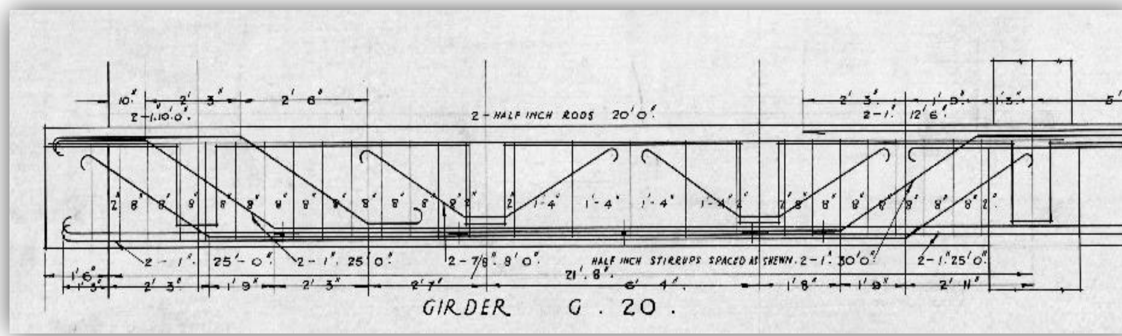

Figure 17 Details showing beam reinforcement (Source: Brisbane City Hall)

A large number of record drawings, both architectural and structural, were available from Brisbane City Council and Brisbane City Library Archives. Figure 17, from a section of the original structural plans, shows typical girder reinforcement. The arrangement of the bars was confirmed by ground penetrating radar (GPR) testing. Unlike the case of modern construction, it appears that most beams were designed and detailed separately as there was very little repetition within the structure in spite of the symmetrical arrangements and almost identical loadings in several locations.

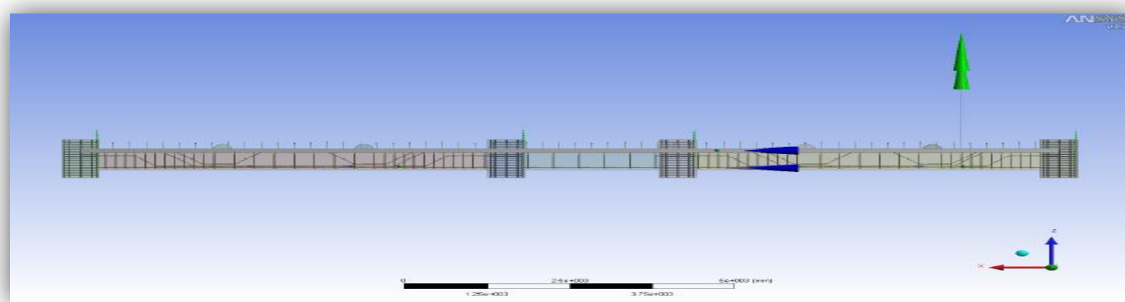

Figure 18 Finite element model for unstrengthened girder (Source: Aurecon)

Brisbane City Hall was not only constructed using obsolete reinforced concrete practice but it was also designed during the time when engineers were using early methods and theories of structural analysis. Nowadays the more popular and faster "finite element method" is available for calculations and modelling, along with the availability of modern computational devices for technical analysis. The term "finite element method" first appeared in 1960 and in a relatively short time became part of everyday engineering language in the abbreviated form of "FEM". Since the beginning of the 1970s it has evolved a greater level of sophistication in its application (Kurrer & Ramm, 2009). The theoretical analysis of the Brisbane City Hall's structure required other computer modelling of structural components. For this analysis, Aurecon used ANSYS application software for the simulation and design process. The FEM was made for both strengthened and unstrengthened girders to demonstrate the effectiveness of the methodology and was created to represent the old structure with the unstrengthened girders (as shown in Figure 18), and then another model was created for the strengthened girders conditions (as shown in Figure 19). For both models, an ultimate imposed floor load of up to 4.5 kPa was applied. This was equal to the agreed load limit of 3.0 kPa multiplied by the load factor of 1.5, as given in AS 1170 and AS 3600.

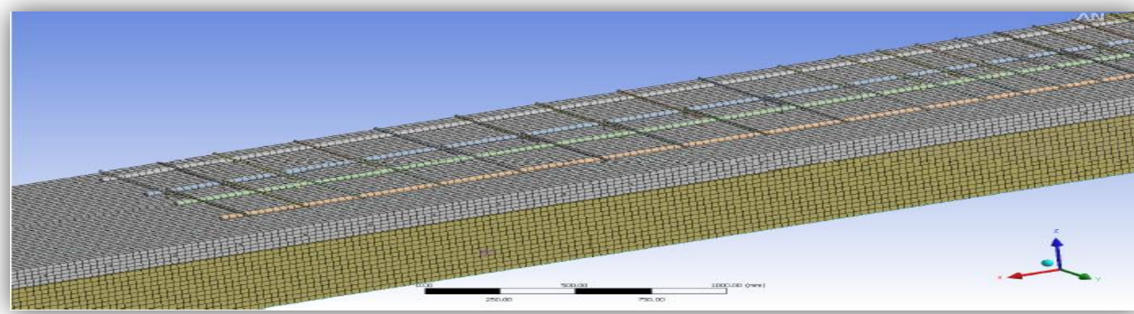

Figure 19 Reinforcement to structural topping (Source: Aurecon)

2.5.1 Ultimate Limit State Computational Analysis

For the purpose of the structural analysis, a conventional rectangular stress block was used to analyse the beams and girders as flanged T or L-sections, and the underlying methodology of AS 3600 was generally used throughout in conjunction with the loads and load factors given in AS 1170. Throughout the process, independent verification was provided by Professor Peter Dux of the University of Queensland.

Table 2 Material properties of existing reinforced concrete of Brisbane City Hall used by Aurecon for analysis purposes (Source: Cartwright, 2012)

Characteristic compressive strength of concrete	3.4 MPa
Modulus of elasticity of concrete	6,785 MPa
Concrete density	2,200 kg/m3
Yield stress of reinforcement	230 MPa
Modulus of elasticity of reinforcement	200,000 MPa

For analysis the properties listed in Table 2 were adopted. Based on the original reinforcement drawings (See Figure 17), the secondary beams were analysed as simply supported, while the primary beams were analysed as having only a nominal continuity at the columns. From this information, the expected concrete compressive strength and the available record drawings, Aurecon undertook an initial structural assessment of the main structural elements coming to the following conclusions. The secondary beams behave in a ductile manner, meaning that the steel reinforcement would gradually deform under tensile stresses. In the event of a structural failure, this would be a gradual process, allowing the building occupants to evacuate before any collapse occurs. The primary beams on the other hand are heavily over-reinforced in the areas where tension would occur. As a result, the mode of failure would be an over-stressing of the concrete in the compressive zone of the beam. Such a failure would be sudden and catastrophic and for this reason compressive failures are not permitted under the current design standards. However the load required to result in this failure was approximately 10 kPa, twice the required imposed floor load, and this was considered to be an adequate factor of safety in normal use (Cartwright & Belperio, 2012).

For both the primary and secondary beams the ultimate load capacity is limited by the shear strength of the concrete sections and typically this was a value of around 2.0 kPa. Although consisting of both ligatures and cranked bars (See Figure 17) and the existing reinforcement is overdesigned in tension, the shear reinforcement used in the existing design was significantly less than the current code requirements. The poor quality concrete also resulted in the shear strength being constrained by web crushing, with the characteristic compressive strength (See Equation 2 below) being the limiting factor.

$$V_{u.max} = 0.2 \times f'_c \times b_v \times d_o$$

where: $V_{u.max}$ .... maximum allowable shear
f'_c .... compressive strength of concrete at 28 days
b_v .... effective breadth of a web for shear
d_o .... distance from the extreme compressive fibre of the concrete to the centroid of the outermost layer of tensile reinforcement or tendons

Equation 2 Equation for obtaining maximum allowable shear(AS 3600 - 2009)

Figure 20 Existing columns and completed overlays of beams and girders (Source: The Soul of Brisbane)

Under the typical vertical loads experienced during the life of the building, Aurecon’s initial calculations suggested that the concrete columns were at, or close to, their capacity (See Figure 20). Based on a 6.0MPa characteristic strength, a number of columns were expected to ultimately fail under combined axial load and bending. The axial column load was further increased by the requirement to move the new Museum of Brisbane onto the roof of the building as a part of the redevelopment. However when testing confirmed the characteristic strength as being 3.4 MPa, this increased the scope of strengthening considerably, both to the beams and in particular to the columns. In addition to increased costs, this would also have compromised many areas of high heritage significance, including the entrance foyers and council chamber. It was necessary for Aurecon, to discuss with the client, Brisbane City Council, ways to reduce the imposed floor load as a means of limiting the extent of strengthening. The critical area of potential loading was the existing function room suite, where large groups of people could congregate. The allowable capacity of this area was already limited and strictly enforced as a part of the fire engineering requirements for the building.

The limiting load in the foyers is determined by practical considerations, as generally it was not practical for more than one function room to open out into the foyer at any one time. In the event of an emergency evacuation, it was not expected that the static imposed load would exceed 2.5 kPa as this represented the maximum load of a densely packed crowd. With the function rooms, dynamic activities will be prohibited in the foyers (Cartwright & Belperio, 2012).

2.5.2 Serviceability Limit State Computational Analysis

Using the Serviceability Limit State computational analysis, both deflection and crack widths were assessed. For typical beams and girders the total deflection was found to be less than span / 250. Crack widths were found to be less than 0.3 mm. Typical results for both deflection and crack widths are shown in Table 3 below (Cartwright & Belperio, 2012).

Table 3 Deflections and crack widths of typical beams and girders under service loads (Source: Cartwright, 2012)

Girder / Beam reference	Span (m)	Δ (mm)		Allowable deflection (mm)	Maximum crack width (mm)
		Short term	Long term		
G13	6.4	8.0	13.2	23.8	0.20
G19	2.6	0.1	0.1	8.6	0.20
G21	5.6	6.0	9.8	20.6	0.10
G24	5.2	5.3	8.6	19.0	0.10
G28	9.8	13.5	23.0	37.4	0.10
B1	6.4	5.1	7.9	24.2	0.09
B2	6.4	4.3	6.8	24.2	0.08
B4	6.2	4.4	6.9	23.4	0.08
B18	6.4	4.4	7.0	24.2	0.08
B20	5.8	3.3	5.2	21.8	0.07
B22	7.4	6.8	10.8	28.2	0.09
B28	3.6	0.5	0.7	13.0	0.04
B29	3.9	0.8	1.0	14.2	0.05
B30	5.8	3.3	5.2	21.8	0.07
B48	6.4	3.4	5.4	24.2	0.06
B49	7.4	4.2	6.8	28.2	0.06

2.5.3 Fire Resistance of Existing Structure

While the building is to be fitted with sprinklers throughout, the possibility of sprinkler failure is rare, but still needed to be considered in the structural design. As a result of both the low concrete strength and the lack of cover of the reinforcement, the fire resistance of the existing structure was found to be low. It is intended to provide additional protection to the floor slabs to achieve at least 45 minutes of structural integrity in the event of a fire. This is considered a life-safety issue as it would provide sufficient time for an orderly evacuation of the building as well as search and rescue operations. Evacuation modelling by the fire engineers and discussions with Queensland Fire and Rescue confirmed that 45 minutes would be adequate for both tasks. To achieve this it is intended to apply a passive fire protection system to the slab soffits so that their structural integrity in the event of a fire matches that of the beams.

2.6 Testing and Results

Figure 21 Water tank filled with water to test beam deflection when subjected to load (Source: The Soul of Brisbane)

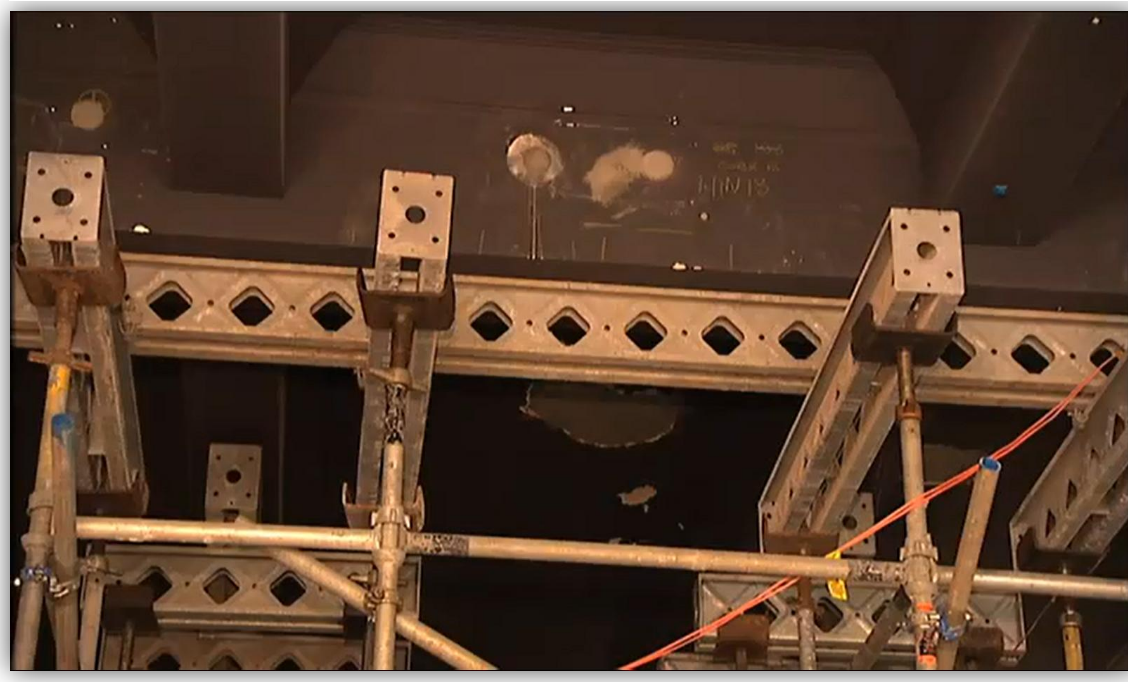

Figure 22 Photograph showing the test of girders under load (Source: The Soul of Brisbane)

Full scale load testing (as shown in Figure 21) was carried out to check if the strengthening had been done correctly between the 26th May and the 8th June 2011.

The test was carried out on level one in the north quadrant of the building (the Balmoral and Oak Table rooms). The objective was to test the typical strengthening works installed on the beams and girders. The soffit of the girders and beams were inspected for existing cracks. The contractor prepared a marked-up plan of the existing cracks in the concrete girders, showing crack width, orientation, location and length.

The beams and girders in the location where the test was to be executed have heavy duty back propping placed under them. A gap of 50 mm was provided between the top surface of the Hyplank and the soffit of the beams and girders in the loading zone. No gap was provided between the top surface of the Hyplank and the soffit of the girders located at the perimeter of the loading zone. Figures 22 and 23 illustrate the testing method that Aurecon devised to ensure the strengthening method was correct.

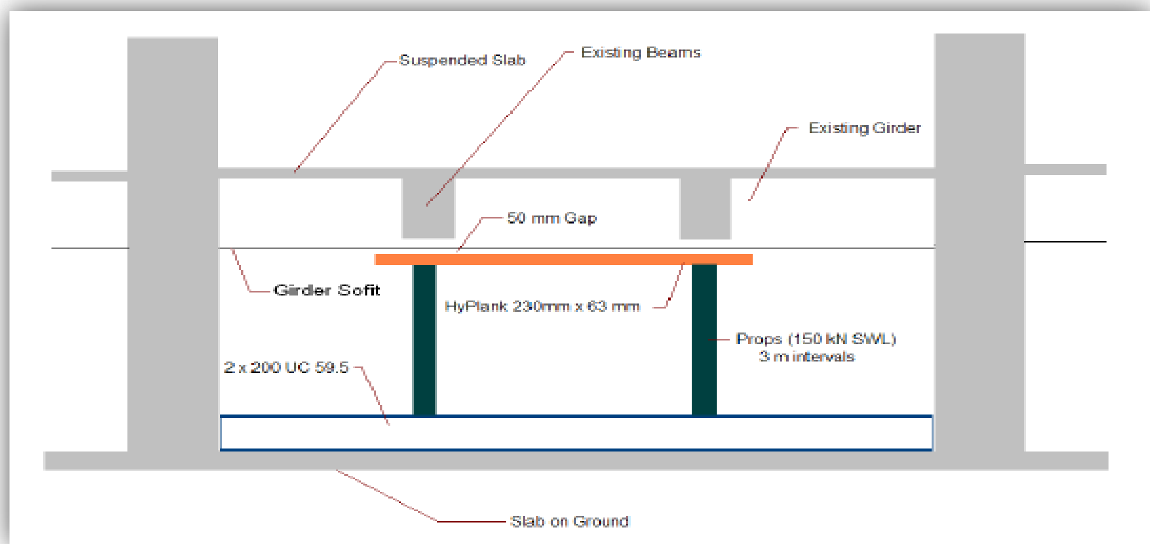

Figure 23 Propping set up devised by Aurecon to check the deflection of beams and girders under loads (Cartwright, 2011)

The results of the load test are summarised in Figure 24, which shows the deflection against the applied load for the onsite strengthened girders, along with the theoretical results for both strengthened and un-strengthened girders (both modelled using finite-element analysis).

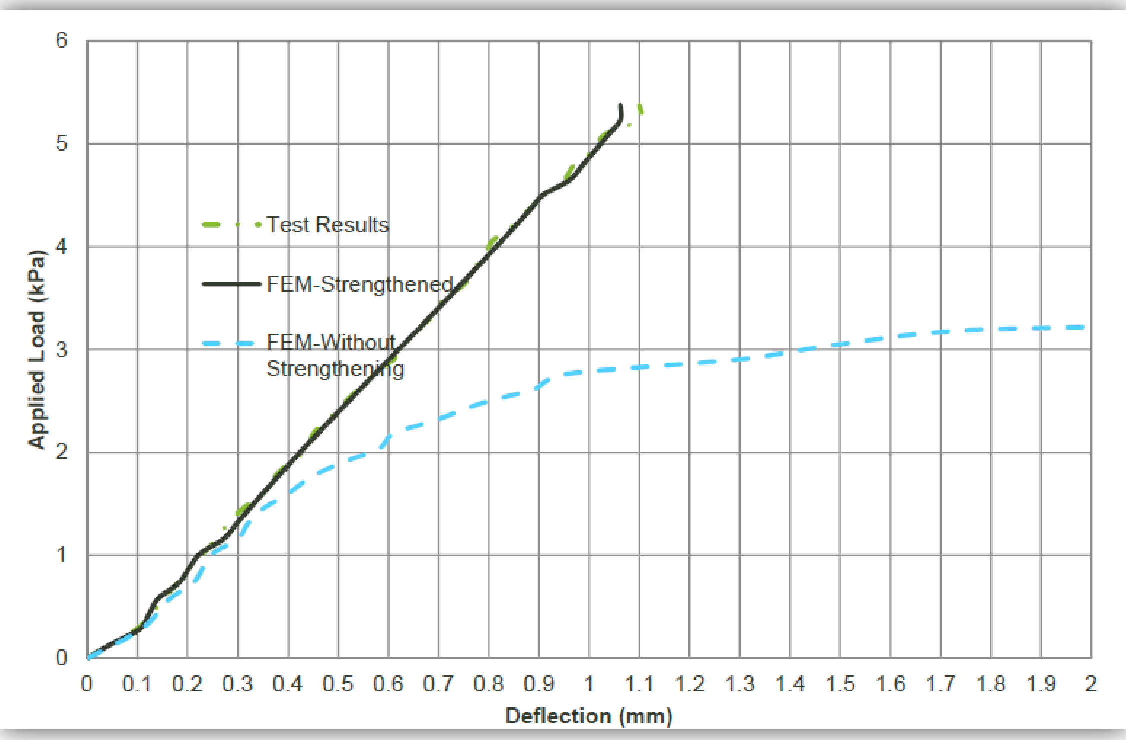

Figure 24 Comparison of the load test with the theoretical analysis (Source: Aurecon)

With a 3.0 kPa imposed floor load, the deflection of the strengthened girder was similar (approximately 0.6 mm) for both the theoretical analysis and the load test. This was a significant improvement over the theoretical analysis of the un-strengthened girder, which had a higher rate of deflection, and which had failed at approximately 3.2 kPa. The measured deflections were well within the generally accepted limiting value of span / 500 (for beams where the line of sight is along the soffit).

A visual inspection of the beams and girders after the tests revealed only fine cracking in the tension zones. This is to be expected in reinforced concrete members where the cement structure has to crack in order for the reinforcement to be effective in tension. As a result of the load test a permanent deflection in the girders of approximately 0.05 mm was recorded.

The full-scale load test demonstrated that the strengthened girders performed in the manner predicted in the theoretical analysis. Based on the results of the full scale load test it was considered that the overlay strengthening strategy has been validated for the agreed 3 kPa imposed floor load. This testing results means that the structural restrengthening upgraded the structural capacity of the beams and girders of Brisbane City Hall. The concrete overlays (see Figure 25) enable the structures to comply with the current building legislative requirements stated on AS 1170 and AS 3600 for building occupancy with an important condition that it will not allow any physical activities such as rhythmic dancing in the function rooms. The dynamic effects of those activities would increase the stresses in the floor structures. This condition was approved by the Brisbane City Council and the structural designer (Cartwright & Belperio, 2012).

Figure 25 Completed overlays of beams and girders (Source: A. Cruz)

3 Comparison to Other Building Restorations

Comparative analysis is one the key research methods for this thesis in addition to historical and interview approach. Four case studies referring to similar structures built within the same time period as the Brisbane City Hall were selected for comparative purposes. Buildings in the USA were chosen to support this research on an international platform.

The triangulation of this techniques namely interviews with experts, historical analysis and comparison with other buildings was intended to bring out the merit of the innovative restorative approach adopted to Brisbane City Hall.

3.1 California State Capitol Building: Structural Reconstruction

Figure 26 State Capitol Building in California, restored 1982 (Source: www.trdrp.org)

For the purpose of this research, the methods used in the restoration of the Sacramento State Capitol (See Figure 26) building have been analysed and were compared to the Brisbane City Hall restoration. The structural reconstruction and conservation works on the California State Capitol Building in Sacramento makes an interesting comparison to the case study of the Brisbane City Hall, although the structural reconstruction was bolder in the sense that the owners renewed the old structural system with a more modern reinforced concrete and structural steel equivalent. They retained the façade by supporting it temporarily while rebuilding the structure from the top to bottom, which was exactly the reverse operation to constructing a new building. The result was a building with an old structural façade and a totally new internal configuration, an edifice which can be compared to an ‘old man’s skin on the bones of a young man’. However this kind of restoration, although guaranteeing a higher degree of safety for the public, does not meet the criteria of many conservation bodies.

Similar to the Brisbane City Hall's circular auditorium, the State Capitol featured a rotunda; its walls supported a brick inner dome and another upper dome consisting of wrought iron bowstring trusses. The scope of the strengthening of the rotunda walls started from the first floor upwards. Only a small portion where the remnants of the original walls were preserved for show to the public. It was also mentioned that the entire floor systems consisting of wrought-iron beams with shallow brick arches in between was removed and replaced during the restoration. The stronger replacement reinforce concrete floor and wall system also enabled the contractors to build scaffolding for the builders to work on the structure's upper levels.

The last major structural reconstruction of the Sacramento Capitol started in 1975 and was completed in 1982, 34 years before the major structural reconstruction of Brisbane City Hall. The Sacramento Capitol was originally constructed of locally-made brick just over a decade after California became a state in 1849; it started in 1860 and was built over duration of 14 years. Because of the high degree of historical authenticity, in 1975 an enacted legislation funded the restoration, amounting to $42 million dollars. Similar to other restorations, there was also opposition by advocates who were rallying for a new replacement structure but the Capitol's significance in United States history outweighed this opposition. A provision in the legislation even included the selection of the contractors on the basis of their qualifications rather than tendering the job in search of the lowest bidder. This provision allowed the contractors to be a part of the design team. Welton Becket was selected as the architect in September 1975 while in the next month a joint venture between Continental-Heller Inc. and Swinerton and Walberg was chosen to be the contractor.

The State Capitol in Sacramento California, similar to Brisbane City Hall, was also closed to the public in order to accommodate its restoration back in the 1970s. Before this restoration, members of the public considered replacing the old iconic building with a more modern structure (Capitol Museum, 2013). The Capitol's restoration was unconventional and it has required coordination of several government departments in order to make it possible to restore the Capitol with a high degree of authenticity. This approach is typical of heritage building repairs and is quite similar in approach to the Brisbane City Hall restoration wherein it has required great collaboration between government institutions such as the Department of Environment and Heritage Protection and the Department of State, Infrastructure and Planning in order to implement the project efficiently.

Sacramento is comparatively less susceptible to earthquakes, unlike its neighbouring city San Francisco. Despite its decreased vulnerability to earthquakes, it was decided that this renovation would have to comply with the earthquake requirements of the time (Worsley et al., 1988). The result was a complete demolition of the internal structure leaving only the skin of the building and the renovation was done from top to bottom. All these innovations and techniques were successfully done and the State Capitol was re-opened in January 1982.

One big concern for the local authority building regulators is that Brisbane City Hall was constructed long before earthquake loads were considered a significant aspect of design standards in Brisbane. In recent years parts of Australia and New Zealand have experienced earthquakes with considerable magnitude. This triggered the necessity for creating provisions that will ensure building safety in the case of such disasters. Currently, “Strengthening Existing Buildings for Earthquake” (AS 3826 - 1998) serves as a guideline for this purpose, however it does not impose any additional design criteria for heritage buildings. An investigation carried out by a concrete technologist, David Beal, revealed the characteristic compressive strength of the concrete in the City Hall to be 6 MPa at 28 days based on core test results (Beal, 2008). AS 3600 also does not explicitly consider concrete with a characteristic strength of less than 20 MPa, although lower strength concrete is within the scope of the standard (Cartwright, 2011). The existing concrete compressive strength of Brisbane City Hall would therefore fail today’s more stringent standards. To ensure that the ongoing restoration will contribute value through the structural rehabilitation, it was important to guarantee that the building after construction will stand and comply with the basic requirements of the current standards. Ian Maitland (2008) suggested it was worthwhile to also apply the requirements of (AS 1170 - 2002; AS 1170.1 - 2002; AS 1170.4 - 2007) – which give earthquake analysis parameters – to the analysis methods for heritage buildings. It is, therefore, important to assess the building on the basis of the current available building standards as building regulations required the upgrade of new and major renovations to comply with all relevant existing applicable standards.

Figure 27 ISCARSAH/ICOMOS expert member and leading conservationist, Randolph Langenbach, commenting on the restoration of Brisbane City Hall. (Source: A. Cruz)

Leading conservationist Mr Randolph Langenbach of ISCARSAH/ICOMOS, offered some advice regarding restoration works in historical buildings similar to Brisbane City Hall. Mr Langenbach discussed restoration works on reinforced concrete buildings in the San Francisco Bay area (Figure 27). Langenbach (2007) stated that “the repeated collapse of thousands of reinforced concrete schools, homes, and apartment houses in earthquakes around the world were also evidence of the fallacy of eternal progress”. Discussing the ongoing restoration of Brisbane City Hall, Mr Langenbach was concerned about the compliance of the building with seismic requirements. He also raised an important issue regarding the concrete overlay method, in that instead of making the building lighter it would add dead load to the structure which would create a negative effect in its seismic resistance(Langenbach, 2012). Another expert from the USA, Mr Donald Friedman of Old Structures Engineering PC, raised concerns about the technique of bonding the new and much stronger concrete to the existing weak concrete without considering shear failure at or near the bonding plane in the concrete overlay method (Friedman, 2012). To overcome this concern, the concrete reinforcement of the concrete overlay will be dowelled vertically to the existing beams or girders.

This major structural renewal of the State Capitol is considerably more extreme than the case of the Brisbane City Hall. While it is considered to be more structurally realisable and straightforward approach, this method is against the basic ideals of ICOMOS which is advocating the use of minimal intervention and the solution and can be easily removable (Roca, 2013). This method known as 'façadism' could have been applied in the case of the Brisbane City Hall but it will surely lose most of its heritage fabric in the process.

3.2 Frank Lloyd Wright's Unity Temple: Structural Repair and Restoration

Figure 28 Photograph showing the west facade of Unity Temple (Source: A. Cruz)

To expand the comparative analysis for this research, some early reinforced concrete buildings in Chicago that were built in the same period as the Brisbane City Hall (1890 to 1930) were explored by means of field inspections and interviews with some local conservation experts to expand the comparative analysis for this research. It is important to note that most of the reinforced concrete buildings that were built in the USA during this time have now been demolished and replaced. This is due to the cultural variations in US traditions for demolition and redevelopment of buildings and sites as compared to Australia in terms of restorations and refurbishment. As the new codes evolved in the States, building control authorities required that the structures be upgraded to code requirements or to be demolished (Harboe, 2012).

One of the most well-known examples of a reinforced concrete structure is the Unity Temple located (See Figure 28) in Oak Park, Illinois. It was completed in 1907 and was designed by Frank Lloyd Wright. Similar to Brisbane City Hall's reinforced

Figure 29 Photographs showing deteriorations of the reinforced concrete structure of Unity Temple (Source: A. Cruz)

concrete structure, it has also suffered deterioration of its construction materials. The condition of the roof slab structure on the west overhang of the church was assessed among other things during the inspection by the author. It also has a problem of water penetration that was the major cause of concrete deterioration (See Figure 29 above) that has required rehabilitation as the result of an investigation completed in 1987 (Gebregziabhier, 2008).

At the time of construction two types of concrete were used, a light weight concrete and normal weight concrete. The elements of the building that resist compressive stresses, such as foundations, walls and piers, were constructed from normal weight concrete, composed of Portland cement, sand and limestone aggregate. On the other hand, the elements that resist flexural stresses, such as roof and floor slabs and the temple overhangs were constructed from light weight concrete, composed of Portland cement, sand and soft coal cinders.

Since one of the major materials used in constructing the building was light weight concrete, the deterioration of the steel reinforcement was at a faster rate due to the ease for water to penetrate, allowing quicker carbonation compared to normal weight concrete because the alkalinity is lower than normal weight concrete, resulting in a decline in the integrity of the steel reinforcement.

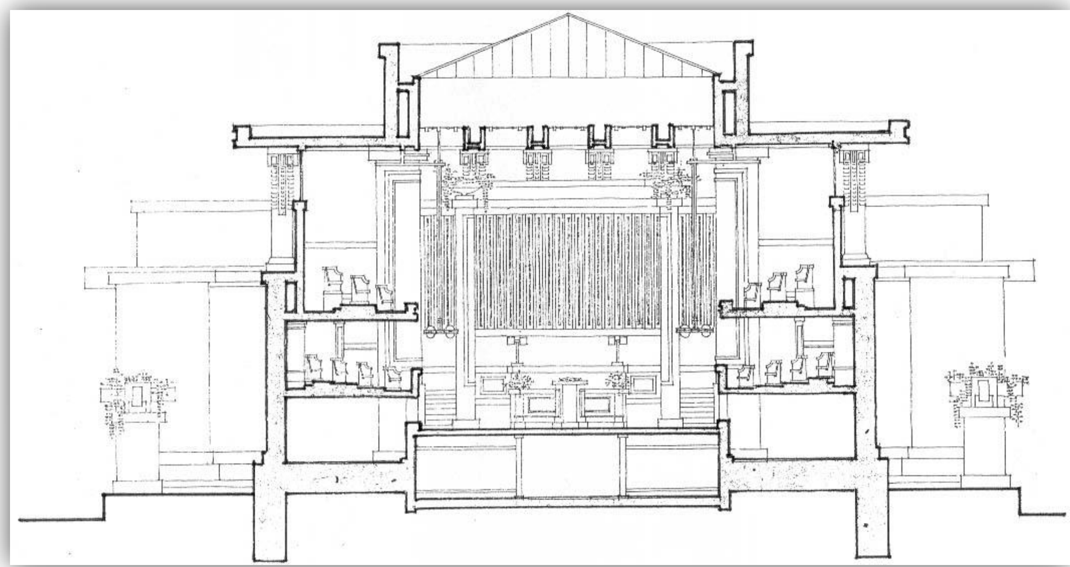

Figure 30 Cross section of the Temple showing the concrete roof slab and the overhang (Source: solopassion.com)

Similar to the case of Brisbane City Hall, the Unity Temple showed evidence of spalling of the concrete to the soffit of the western temple overhang, which resulted in the reinforcing steel to be exposed. It was also evident that the fascia on this overhang indicated that the majority of the parts had been delaminated. This showed that water was able to get in through these flat roof areas and condensation would be able to reach upward from the bottom layer, causing the deterioration of the supports (See Figure 30).

Laboratory analysis of the concrete specimen from the west overhang also indicated that the concrete used was of a high water-cement ratio, causing the concrete to be porous and weak. Furthermore, the concrete was fully carbonated and contained significant amounts of chloride (Gebregziabhier, 2008). During the early 1970's, the damage on the overhang called for repairs, so a rehabilitation program was initiated and done in the same period. The above integrated damages/deterioration on the west overhang caused loss of strength in the overhang slab, which necessitated the repair of the overhang.

It is interesting to note that the original specification for Unity Temple included general criteria for bar placement of floor and roof slabs, but gave no indication of the reinforcement size and placement within the cantilever slab which forms the west overhang of the temple. Frank Lloyd Wright must have overseen the proportion of steel requirements for overhanging beams. That is probably because the standards for reinforced concrete had not been developed and a lot of US concrete practice before 1930 was based on patented, proprietary systems (e.g., the Kahn System). The remainder was based on either the Joint Committee reports or conservative versions of the reports in local building codes (Friedman, 2012).

3.3 The Fallingwater Restoration and Repair

Figure 31 The reinforced concrete overhangs of Fallingwater (Sourse:Smithsonianmag.com)

For a specific comparison of reinforced concrete buildings, the case of Fallingwater (Figure 31) designed by Frank Lloyd Wright, were studied and analysed. These buildings were included heritage listing of reinforced concrete structures in the USA, as despite abundance of reinforced concrete structures, most fell short of being deemed historic and/or 'modern heritage' (Harboe, 2012). Additionally these aforementioned buildings appeared after study to have similar problems and deteriorations to Brisbane City Hall and also recently needed to be restored as a result.

Fallingwater is another Frank Lloyd Wright masterpiece and is a good example of the early use of reinforced concrete. It was designed in 1935, with the building work being started in 1936. It was originally owned by Edgar Kauffman Sr. who was a successful department store owner in Pittsburgh. His son, who worked as an apprentice in Wright's studio at Taliesin, convinced Kauffman Sr. to retain Wright to design Fallingwater following some work he had been commissioned to do with the store. It was originally a weekend family house for the Kauffmans, built on their wooded property that featured a small stream. The family assumed that this house would be built downstream from the ledges with a view of the waterfalls from below, however Wright managed to design the house and situate it above the falls on a large sandstone ledge overlooking the stream (Atkins, 2009).

This house was commended for its concrete terraces hanging over a stream. Unfortunately the hanging concrete terraces failed shortly after it was built and gradually continued to sag considerably over the next six decades, prompting the owners, Western Pennsylvania Conservancy, to hire engineers to inspect the structure. This structural investigation in 1995 revealed that the design did not provide enough support and as a result, the reinforcement beams were bending leading to the concern that it would collapse if no action was taken. The following year, while the rehabilitation design was being devised, they decided to install temporary beams and columns. The Conservancy hired experts to investigate and undertake the design for Fallingwater's permanent repair scheme. It required the use of radar and ultrasonic pulses to investigate the building's structural problems (Silman & Matteo, 2006).

The design was a structure built on four large bolsters at the fixed end of the cantilever beam, three of which were reinforced concrete and the other one which was stone masonry. Each bolster supported a horizontal reinforced concrete beam that extended 14.5 feet beyond it. Four inch wide concrete joists held the beams together. A concrete slab beneath the joists and the cantilever beams served as the finished underside of the building. This concrete slab under the cantilever beams was placed to increase the resistance to compression, thereby raising the structure's capability to endure greater load. Fallingwater was composed of several cantilevers, from the terraces that extended from the east and west side of the first floor to the master's bedroom on the second floor which jutted out six feet further southward than the terraces on the first floor (Feldmann, 2005).

Concerns were raised as early as the building's construction, Metzger-Richardson, who was supplying the steel for the reinforced concrete, insisted on doubling the bars in the cantilever beams below the living room, to make it strong enough to resist bending. Wright on the other hand defended his design and expressed his opinion that the additional bars would just increase the weight of the beams and stubbornly stood by his original plan, even though it would have clearly failed if not for the Metzger-Richardson addition (Silman, 2000). But the additional steel bars apparently were not enough to support the structure either. After the wooden formwork beneath the concrete on the first floor was removed, there was an instantaneous downward movement of 44.5 mm, which was significantly unusual. It was later on reported that the engineer, Mendel Glickman, calculations overlooked the negative reinforcement that balanced out the negative bending moment which caused compression in the lower part of the cantilever beam and tension on the upper part. This resulted in the vulnerability of the cantilever beams to compression caused by the negative movement. The situation was aggravated upon the completion of the second floor where two cracks appeared right after the workers removed the formwork from the concrete of the master bedroom terrace. In the following year, 1937, the Metzger-Richardson firm conducted a load test on the structure and calculated that the tension in the cantilever beams was beyond the safety standards at that time. Given this result, the firm suggested placing permanent props in the streambed to reinforce the first floor and therefore decreasing the length of the cantilevers. Mr Kauffman decided to go with Wright's original design but hired a surveyor to monitor deflections by recording the elevations of the tops of the parapet walls because he was at the same time concerned about the tilting of the terraces. After Kauffman Sr.'s death, his son presented the house to the Western Pennsylvania Conservancy (Silman & Matteo, 2006).

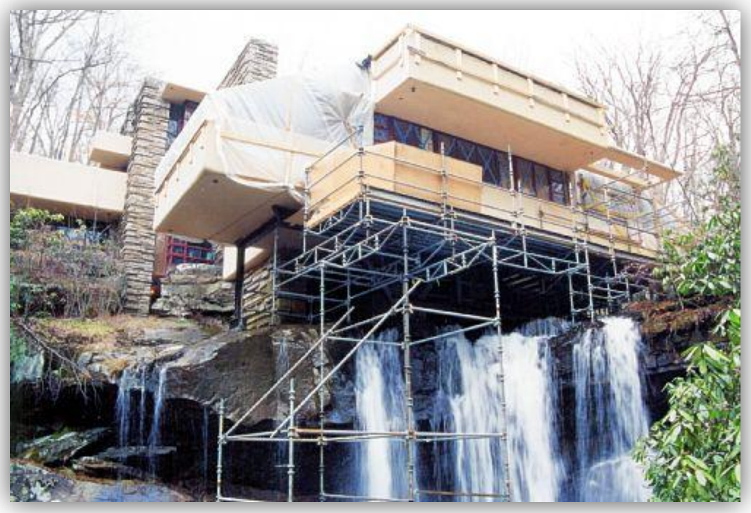

Figure 32 Photograph showing the temporary scaffolding during the strengthening of the cantilever beams of Fallingwater (Source: blog-arq.com)

The Conservancy at that time wanted to establish if it was a good idea to repair the cracks cosmetically without structural review. They employed Robert Silman and Associates to address the building's issues. They used a "water level" to take height readings at several locations to compare with the previous readings. This yielded a measurement reading of as much as 184 mm of sagging on the edge of the east terrace and 146 mm on the west terrace. It also revealed that the deflection on the south end of the master bedroom terrace was about 114 mm (Silman, 2000).

To successfully design a maintenance scheme, the firm investigated the structure's compliance to Wright's original design in order to properly identify the number of, and location of, the reinforcing bars in the cantilevers and other structural elements. The firm used instruments that used impulse radar, ultrasonic pulses and high-resolution magnetic detection to plumb the interiors of the beams, the floors and the parapets. This process also enabled the firm to identify the quality of the house's concrete. A similar approach was used with the restoration of Brisbane City Hall when Aurecon used GPR to confirm the existing location of reinforcement in compliance with the original plans.

Robert Silman and Associates also made use of computer modelling analysis to test three assumptions. First, that the master bedroom terrace could support itself through the cantilever. Next, that the living room was a self-supporting cantilever and finally, that the living room could support both itself and the master bedroom terrace. Based on the analysis, it was revealed that the first scenario was not possible since the stress in the reinforcing bars was four times the steel's yield strength. From this result, the firm was able to determine that while the living room was a self-supporting cantilever and was able to support the weight that induced tolerable stresses, it also had to support the master bedroom terrace. Given this analysis, it was concluded that the stresses were at critical levels since they were about the same as the yield strength of the materials. Other factors such as shrinkage and creep were added on to the calculations and the result was that the failure in the design was brought about by a chain of events during its original construction. It appeared that the engineers thought that the master bedroom terrace could not support itself so they redesigned the mullions to take on some of the load but they failed to alter the main cantilever beam's design to carry this extra load (Silman & Matteo, 2006).

When these findings were submitted to the Conservancy, they decided on a permanent repair to address all the structural issues and lengthen its service life. They also headed to Robert Silman and Associates for advice on shoring up the ends of the main beams while the repair was being implemented in order to prevent the house from totally collapsing before the rehabilitation was completed. In 1997, the workers installed inconspicuous steel columns and girders from the streambed to the underside of the first floor. The sandstone ledge was also braced with pipe struts in the cave behind the falls. This shoring supported the house and kept it temporarily safe for visiting tourists until all the renovations were done (Silman, 2000).

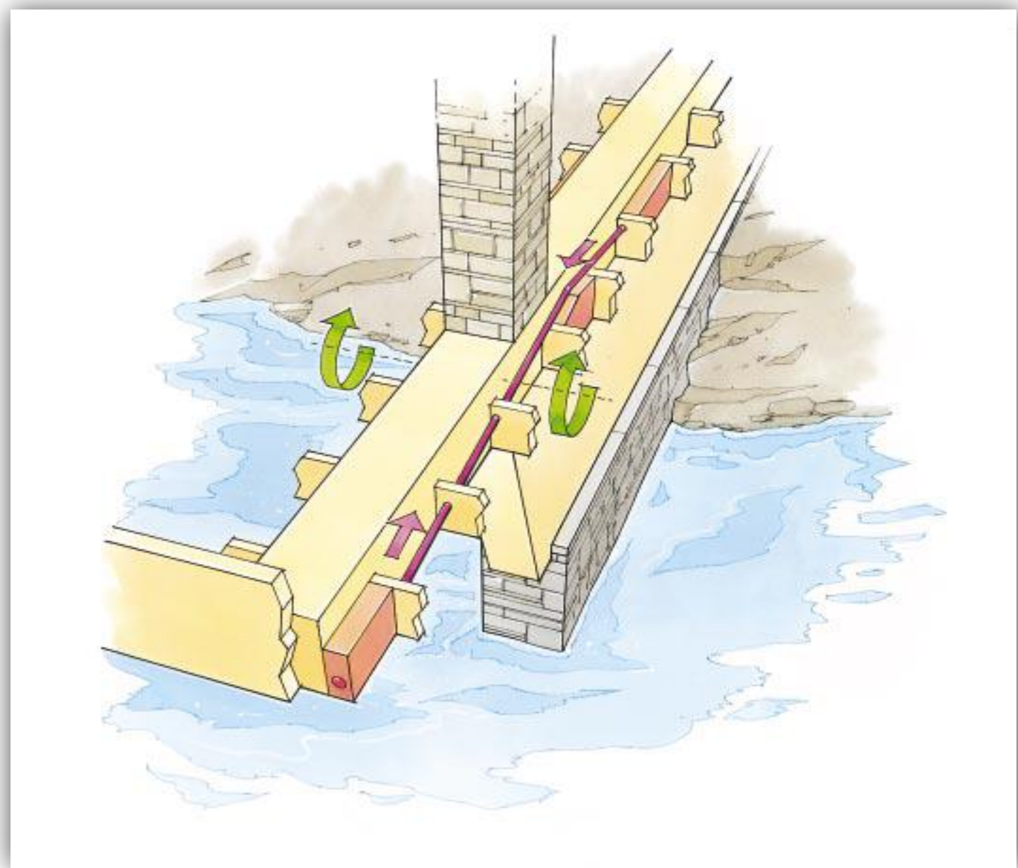

Figure 33 Strengthening method devised to strengthen the cantilever beam of Fallingwater (Source: Robert Silman & Associates)

In order to avoid altering Fallingwater's appearance, the repair included reinforcing three of the four cantilever beams below the living room by post-tensioning or connecting the beams to steel cables and using the tension in the cables to relieve the stress on the beams (See Figure 33). The repair also necessitated removing the stone floor of the living room temporarily in order to access the three main cantilever beams. Concrete blocks were attached to the south ends of each beam in which a hollow duct was inserted. Alongside the beams, the ducts run alongside upward and extend through holes that were drilled on the concrete joists. The cables exerted positive bending moments to counteract the negative moments caused by the cantilever actions while the overstressed concrete joists on the second floor were reinforced through bolting steel channels and by bonding carbon-fibre plates. To finish the repairs, the holes were patched and painted, the stone floor was replaced, the temporary shoring was removed and the cracks filled up (Silman, 2000).

3.4 The Holy Family Church

Figure 34 Photograph showing the façade of the Holy Family Church, Chicago (Source: A. Cruz)

The Holy Family Church building (See Figure 34) was chosen for comparative analysis to explore issues regarding minimal intervention and its benefits. Often the maintenance of a building is focused on visible deterioration and can overlook the underlying cause of the corrosion, resulting in more serious damage to the structure. In these instances, it is imperative to trace the root of the impairment in order to enhance fully the service life of these older buildings. The conservation of this church was an example to demonstrate the importance of fully investigating the whole assembly of a heritage building, to ensure economic benefits and also overall implementation success. Its failure was rooted in the lack of a quality maintenance system that would have ensured care for the water-shedding systems. It would also have been more stable if the materials that were used for the maintenance and repairs were compatible with the characteristics of the original (Crowe, 2007).

The Holy Family Church in Chicago is a classic example of greater deterioration being caused by previous restorations and maintenance. 'Father Jerry', the current parish priest of the Holy Family Church, reiterated in an interview with the author that the main reason for the failure of the former rehabilitation was the shortfall of funds that had been expected from a promised donation; because of this the restoration scheme was not followed as per the specifications. The firm WJE Inc (Wiss, Janney, Elstner Associates Inc) had since completed the latest restoration which undid the previous inadequate repairs and instigated a more suitable repair scheme.

The International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) of ICOMOS outlined a set of recommendations for the analysis and restoration of historic structures which was officially adopted by ICOMOS in 2003. The recommendation promotes a more specific authenticity that is associated with the structures. The recommendations state that the value of a historic building lies not only in the appearance of its individual elements, but also in the integrity of all its components as a unique product of a construction technology characteristic of a time and place (ICOMOS Charter, 2003).

The second oldest church in Chicago, the Holy Family Church showed deterioration in the columns of the church's sanctuary and its south façade appeared to be leaning little more than a decade after it was built in the 1850s. The Holy Family Church was one of only five buildings near the centre of the city that survived the Great Chicago Fire of 1871. Because of the structure's age, in 1984, the Holy Family Preservation Society was established with the goal to repair and restore the church's old glory. The society was able to raise $4.5 million to fund its rehabilitation, but the restoration was centred primarily on the main building rather than the bell tower.

By 1999 the condition of the structure had worsened and showed further signs of deterioration. Deformities on the exterior metal cladding were visible and the interior tower suffered extensive efflorescence while water stains were seen on the timber framing. These prompted an inspection on the ageing structure. Although there were insufficient records regarding maintenance and the original drawings were lost, anecdotal accounts on its repairs provided some information on the works

Figure 35 Photographs showing the decay, previous repairs and the new metal waterproof casing for the cornice of the Holy Family Church Bell Tower (Source: Wiss, Janney, Elstner Associates)

done on the structure. The preliminary investigation revealed that the building was generally intact but to ensure its stability and longer service-life, a rehabilitation scheme was devised. The initial contract was based on the findings from the preliminary inspection. The maintenance work included addressing the issues of the weakened metal cladding, loose sheet metal components that were in danger of falling and the moisture infiltration that was found to have been occurring for an extended period of time. The detail of the contract included costs amounting to $1,085,000 in the initial budget for 3,000 square feet of cleaning, painting and replacement of cladding, 1,000 square feet of wood-sheathing repairs and 1,300 square feet of exterior masonry work. This also covered cleaning the interior and the installation of stairs, landings and lighting. In 2001, scaffolding was erected to be used as a work platform, not just for the restoration process, but also for inspecting the structure more thoroughly. This investigation revealed that the maintenance jobs applied to the structure for the last 125 years were superficial. It was also evident that the source of moisture that caused the deterioration of the masonry walls near the bottom of the sheetmetal cladding was from above, since the masonry on the lower portion of the tower was intact. Earlier repairs on the masonry frieze below the sheetmetal had included installation of a cement-rich parging on the face of the brick (See Figure 35). The Latin cross was also recreated. Replacement bricks were used for this rebuild rather than placing a special order for the original type of bricks.

Changes in the temperature, wind loading and loosened nail attachments created a gap that allowed moisture infiltration. The corrosion extended into the bracing members which caused the deformation within the metal cladding on the northern elevation. These bracings were replaced by built-up preservative-treated members. Variation in the weather conditions was a major factor that affected the service life of the structure. The deformity in the cladding, the decay in the timber on the north side and the loose metal cladding system on the south side of the tower were clear indications of how nature impacts the stability of the building through sun and weather exposure. The moisture infiltration as a result of the restrained thermal movement affected the north elevation more than the south elevation where the temperature was warmer generally because the southern exposure to the sun allowed the framing systems to dry, unlike the north elevation, which did not receive direct sunlight. Previous installation of patches softened the profile of the tower and as a result, it was easier for moisture to get through and loosen the cladding, thereby creating the necessity to clad the seams in order to provide a waterproof barrier. Sealant repairs had been done to somewhat resolve the issue in the roofing system but it seemed that the application was not properly executed. Additionally, it appeared that the sealant did not adhere well to the epoxy-paint coating applied to the sheetmetal prior to the sealing process. The difference in the characteristics between the paint coating and the elastomeric sealant caused this problem. Paint coatings typically cure to a hard finish to result in a brittle shell while elastomeric sealant is intended for elasticity and movement. Moreover the dirt and leach polymers from the paint coating were absorbed and collected by the soft sealant.

Given these details the repair that was called for and implemented in 2001 included the installation of a concealed butyl sealant joint that did not require painting. Riveted joints were used in areas that did not require movement allowance. These rivets strengthened the material connection and avoided the failure in the sealed assembly. Any repairs are just futile attempts to correct issues if the underlying materials have deteriorated. This was the case with the tower. The maintenance work implemented on it, instead of enhancing the service life of the structure, only trapped moisture in the walls, making it vulnerable to corrosion. The variations in the materials used for patching also contributed to the tower's overall deterioration. Galvanised steel, aluminium and terne-coated stainless steel were used in the patching job done on the tower. Previously installed coating applied to the cladding apparently separated these materials and the terne-coated stainless steel lacked proper surface preparation (Crowe, 2007).

Minimal intervention in the restoration may retain the most fabric of the building and is the suggested and encouraged approach by the ICOMOS, but often instead of upgrading the service life of the structure this limited rectifications caused more damage because the underlying cause of deterioration was not sufficiently addressed. As in the case of Brisbane City Hall, the case of the leaking flat roof in the case of Brisbane City Hall has been subjected to cosmetic repairs such as patching and painting on its previous repairs before this major restoration. This had caused serious corrosion of the concrete reinforcement underneath. The inadequate repairs of the past had caused more deterioration that has required this major re-strengthening and restoration as a result.

The itemised four comparative studies highlighted the different approaches with regards to the repair of heritage buildings. These recent restorations highlighted the developments of methods in restoring heritage buildings. Each case study had evaluated its merits and limitations as compare to the ongoing restoration of the Brisbane City Hall.

4 Results

During the course of this research historical analysis, interviews and field inspections to four comparative case studies to Brisbane City Hall restoration, were completed. The results are enumerated in Findings, Conclusions and Recommendations.

4.1. Findings

Four restored buildings were investigated and were used as points of comparison to the case study. First, the State Capitol building in California used a very daring approach of replacing the whole structure of the building while retaining only the skin; the method known as façadism. While this method was considered more reliable in terms of structural safety, it does not promote the ideals of the ICOMOS which is to use minimal intervention on the structure and retain the majority of the original fabric of the building. It is interesting to note that even though Sacramento is considered to be not susceptible to earthquake, the main reason for using this method was to prevent seismic risk.

The second building reviewed was the Unity Temple, a reinforced concrete building which suffered severe deterioration similar to the Brisbane City Hall. This case revealed the common problem of reinforced concrete deterioration that is commonly known as ‘concrete cancer’.

The third building also by Frank Lloyd Wright was Fallingwater, a reinforced concrete building designed by Frank Lloyd Wright. This building required re-strengthening similar to Brisbane City Hall. However, the re-strengthening method used here was to incorporate tension cables to prop up the sagging cantilever beams.

Finally, the Holy Family Church in Chicago used very minimal intervention in the restoration and retained the most fabric of the building. However, instead of upgrading the service life of the structure, this minimal method only caused more damage, mainly because the underlying cause of deterioration was taken for granted and the focus was placed heavily on the cosmetic appearance of the building. While minimal intervention is the most suggested and encouraged approach of the ICOMOS, this method also imposes more maintenance requirements on a building. Oftentimes the repairs can later require further repair jobs to undo the previous ones.

There were three major causes of the ‘concrete cancer’ in case of Brisbane City Hall, typical of heritage reinforced concrete buildings. These were corrosion of the reinforcement, carbonation and alkali aggregate reaction. Because of the ingress of water, the reinforcement steel of the concrete became vulnerable to reactions with chloride and carbon dioxide in the concrete and surroundings. The spalling of concrete and eventually the insufficient cover of the support beams and girders further exposed the reinforcement to the environment which led to corrosion and weakening of the structure.

Brisbane City Hall was built during the advent of reinforced concrete. It was the trend at that time and there were no standards to guide the designers about the implications for the future. Nowadays increasing numbers of reinforced concrete buildings are being listed as heritage buildings. While these buildings are becoming more dangerously out-dated in terms of current building requirements, such as the structural capacity requirements in the Building Code of Australia, there is a growing desire to conserve this type of building.

Before the restoration, there was a notion that the building was subsiding and there was a stream under the foundation of the building but findings showed that it was instead a leak from the flat roof of the Brisbane City Hall that was causing the deterioration of the concrete structure. This leak made its way into the concrete reinforcement, weakening the structural capacity of the building. To mitigate the cause of the problem, tanking of the concrete flat roof was done to ensure a watertight structure that will have no chance of leaking in the future.

There were no strict standards for reinforced concrete at the time when the Brisbane City Hall was built. A lot of reinforced concrete practice was based on patented, proprietary systems (e.g. the Kahn system). The patented systems were more problematic, as there were probably international patents as well, and many of those manufacturers insisted on producing their own rebar rather than licensing.

Based on the recent tests, the compressive strength of the concrete of Brisbane City Hall was only 3.6 MPa. This is extremely low for stone-aggregate concrete by today’s standards. Reconciling this with the current standard was a great challenge for restorer and conservator. The compatibility of the concrete overlay method, utilised in the Brisbane City Hall renovation, will test the use of this system for heritage structures that is bonding new and much stronger concrete to the weak original concrete without worrying about shear failure at or near the bonding plane.

The current engineering standards are not fully applicable to historic and heritage buildings, as most of the fundamental parameters are beyond the scope of the current standards. Most of the materials and techniques are being superseded by the evolution of technology. Upgrading the heritage buildings to the current standards would require digging up past literature and revisiting old ways of doing things, such as using the long hand approach to building construction restorations and renovations. By examining the current building regulations and standards available, we can establish what is applicable to restoring heritage buildings. This research was able to identify that heritage buildings constructed in earlier times generally fall short of the scope of the current standards for example in the aspects of safety, fire-resistance and structural integrity. However, as the building industry is bound by the current standards, if older historical buildings are to be preserved, it needs to look for innovative ways and/or change the use of the buildings in order to achieve minimal intervention for restoration.

Regarding the recent restoration of the Brisbane City Hall, this research was able to determine that the result of the restoration would be able to meet the current structural requirements. One restriction is in the use of the function rooms that will not allow physical activities, “In the function rooms it will be necessary to prohibit physical activities such as aerobics or rhythmic dancing. The dynamic effects from these activities would increase the stresses in the floor structures” (Cartwright & Belperio, 2012). This condition was approved by the designer and the client so that the final imposed load on the floors would be 3 kPa as opposed to the value of 5 kPa for dance areas with possible halls and studios (AS 1170.1 - 2002). So in effect, a combination of the concrete overlay and the prohibiting of dynamic activities in the function rooms will make the new restoration compliant with the current AS 1170 and AS 3600 requirements.

Several techniques are theoretically available for the restoration of reinforced concrete heritage buildings; including concrete overlay, fibre reinforced polymer (FRP), external post tensioning, span length shortening, steel plates, etc. However the compatibility of the old reinforced concrete is still unknown as the bulk of this type of heritage building is just beginning to appear in the registers. There are relatively few engineers involved in the movement of the restoration of heritage buildings compared to other areas of the profession. Traditionally engineers are reluctant to work on preservation and restoration projects because of their obligation of safety to the public. In addition, the new curriculum, and even the definition and philosophy for the newly emerging “heritage engineering” is still in the stage of being framed (Mateo, 2011; Woodcock, n.d.).

4.2. Conclusions

There was an option to demolish Brisbane City Hall and replace it with a new building, or alternatively the Council could have attempted to demolish the whole internal structural frame, retain the façade and rebuild the building from top to bottom. This option was not however in accordance with the principles of conservation set out in the ICOMOS Burra Charter. Instead, with the available technology and the guidelines of the Burra Charter, there was an attempt to limit intervention and weigh up the bolder solution of preserving the heritage fibre of the building as much as possible. The strengthening method that was devised to restore Brisbane City Hall is in compliance with the principles of the Charter which is to stabilise the structure with minimum intervention.

The method that was used for the ageing frame of Brisbane City Hall’s structure was to drill and graft new concrete overlays and steel reinforcement to it. In spite of the expected deterioration due to the corrosion of the old reinforcing steel, the restoration will give the building an added life in the vicinity of 50 years before another structural overhaul is required, according to the structural designer group, Aurecon (Cartwright & Belperio, 2012).

The principle of structural overlay is a proven theory and has been previously applied to major structures such as bridges. However, when it was applied to a heritage building, some cynicism was raised as to the compatibility of the strengthening solution, specifically the bonding to the old concrete built in a different age, under different conditions and standards.

The process of investigation into the restoration of the Brisbane City Hall should not stop after applying this innovative solution. Based on this study, it will require ongoing monitoring to gain a deeper understanding of how the building will react to this new applied solution. By the time this thesis is completed and published, it is envisioned that the three year restoration work on Brisbane City Hall will have been completed. The innovative solution for strengthening this aging building has utilised the latest computational technology and best available standards and will hopefully give this important iconic Queensland building a new lease of life. Considering that the odds of a major catastrophic disaster such as an earthquake are low, the interim period of 50 years could be a sufficient time for another advanced innovative solution or even a cure for ‘concrete cancer’ to become available. At that time, it may be possible to undertake further investigation and apply future improved solutions to extend the life of the building further. Only post analysis, observations and further research will confirm the integrity of the innovative techniques used on Brisbane City Hall in the restoration described in this study.

For the future it will be beneficial to dig deeper by way of analysis, observation and comparison to confirm the ultimate validity of innovative techniques being used in structural strengthening of historic and heritage buildings. This research has contributed to the recording of the improvements and discrepancies in the way that the Brisbane City Hall restorations are currently, and have historically been, undertaken.

Heritage engineering, also known as preservation engineering or conservation engineering, is still in its infancy. Developing accepted universal restoration methodology, standards, curriculum and definitions are still in development. In spite of the absence of clear and definite codes and standards, engineers are finding innovative new ways to preserve the significant heritage buildings. This investigation of new frontiers has resulted in many innovations, and provided appreciation and new visions of processes to restore old historic buildings.

Currently, heritage building restoration has lagged behind the evolving building standards and regulations. The applications of current building standards were very restrictive to the ways these old buildings have been maintained or restored. As in the case of the Brisbane City Hall, AS 1170 and AS 3600 are just some manifestations that these standards were developed to specifically cater to modern buildings. In spite of this, building operators are required by law to comply with this strict building regulation which refers to these above mentioned standards specific for general concrete structures. The necessity to comply with these standards and to conform with the guidelines of the ICOMOS lead the engineers of Brisbane City Hall to discover innovative ways for re-strengthening heritage buildings which is the concrete overlays.

It is often convenient to assume that demolishing older buildings and constructing new state of the art replacements may be more economically viable and more appealing to the community. However as the society becomes more respectful towards the heritage value of their surroundings as well as environmentally conscious, the consideration of restoration becomes an increasingly sought option. Overall the restoration of the Brisbane City Hall has successfully resolved the problems of water ingress coming from the concrete flat roof, mitigated the severe deterioration of the reinforced concrete and re-strengthened the structures to conform to the current standards.

4.3. Recommendations

Many buildings constructed at the turn of the 20th century are challenged to meet the demands of current usage while progressively deteriorating. The problems in restoring reinforced concrete heritage buildings are evolving; we are continuously learning new ways to solve the problems, whether systematically or technologically. As we explicitly express our interest in ensuring the continued and appropriate use of heritage buildings in order to preserve their life and integrity and guarantee their important and iconic status within the city, this study also recommends a diligent monitoring of the recent restoration of Brisbane City Hall as well as dedicated ongoing research to attain this goal. While the proper solution is in the process of monitoring and verification seeking, I would suggest implementing a more rigorous maintenance program, which is often neglected.

More particularly, it is recommended that a comprehensive review with the current building standards with regards to heritage building structures be conducted to formulate new guidelines so that restoration work will be able to catch up with the evolution of technology. The use of a more holistic approach in dealing with heritage buildings, because of their complexity and vulnerability, is also recommended.

This research has attempted to validate the structural integrity of the applied structural innovation through historical exploration, comparative analysis, field inspections and interviews with the experts who were involved directly or indirectly in the restoration of Brisbane City Hall. However, due to the time constraints, funding supports and premature availability of the data that can only be obtained in the post monitoring stage, the extent of this research has been limited only to the investigation and evaluation of the recent Brisbane City Hall restoration. Nevertheless the drive provided by the initial structural assessment will not stop after applying the innovative re-strengthening solution of concrete overlay. Normally this technique, which included the addition of reinforcement and extra concrete cover, has been used on bridges and newer reinforced concrete structures that have experienced loss of strength due to overloading, however this method of using concrete overlays is a new application in the case of a historic building. This new innovative use of an existing technique tests the compatibility of merging not only old and new materials but also reconciling new and superseded technology and methods. However, post-monitoring, observation and further verification is necessary to confirm the validity of this chosen method (Kelley & Look, 2005; Roca, 2011; Schueremans et al., 2003) to make sure that it is compatible with buildings like Brisbane City Hall.

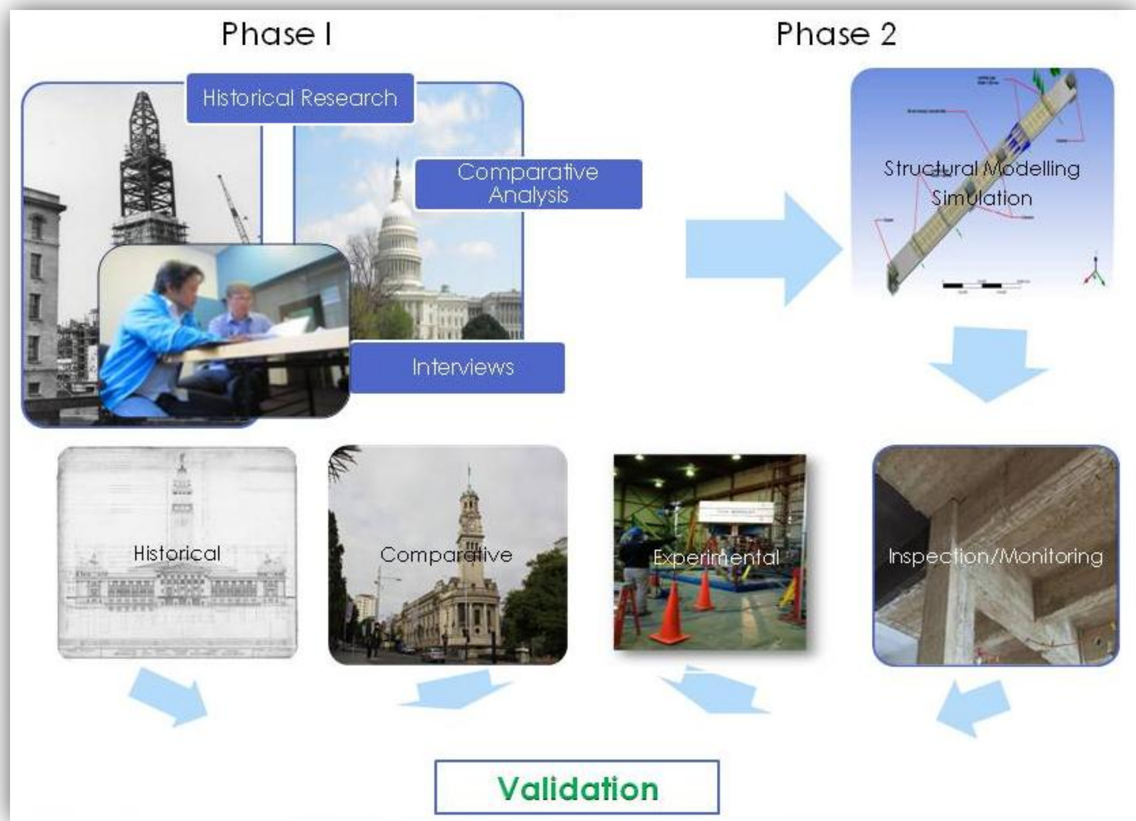

Figure 36 Proposed future research to explore on the compatibility of Structural Modelling Simulation and Validation

Further investigations such as mathematical simulation, monitoring and inspection, experiment and exploration by comparison with other buildings should be done to ensure the future of the Brisbane City Hall heritage building (See Figure 36 above). The ultimate integrity of the innovative methods that will come out in the post-restoration phase will provide more sources of relevant data and information. This will guarantee that this research project will not only document the important aspects of restoration projects but it will also contribute to the new knowledge regarding the restoration of heritage buildings such as Brisbane City Hall.

Further research escalation will explore more on post monitoring and experimental approaches. This could involve the testing of materials and technology compatibility in institutions like CSIRO in Australia, the shaking table laboratory in the Pacific Earthquake Engineering Research Department at the University of California, Berkeley and the similar shaking table laboratory in Japan. Otherwise, the interview techniques and comparative analysis combined with historical analysis could be extended in heritage buildings locally or in New Zealand where extensive structural modification and restoration has been going on. This would validate not only the compatibility and effectiveness of the simulation tools used in the structural analysis but also confirm the integrity of the innovative solution such as the concrete overlay applied to the Brisbane City Hall.

There are several state-of-the-art techniques, both in theory and in practice, in building assessment and strengthening; however the approach for historic structures requires very meticulous and comparatively conservative methods. It is not often that a reinforced concrete structure is considered a historic building, compared to masonry, cast/wrought iron and timber structures. Due to the concrete decay seen, several techniques for strengthening and repair have been developed. The case study of the Brisbane City Hall assessment and restoration will contribute to the opportunity to further explore the restoration of early reinforced concrete.

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